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Stock assessment of rock sole and English sole in Hecate Strait for 2000/2001

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Abstract

We summarize biological information and analyse catch-age data for stocks of rock sole and English sole in Hecate Strait. Our analysis uses a state space catch-age model to reconstruct stock histories. Results indicate that recruitment and biomass of both species have declined over the last four years. In particular, recruitments in 1998 and 1999 reached a historic lows for both species. We compare biomass estimates from the catch-age analysis with those obtained using swept-area expansions of commercial and research survey catch rates. All analyses show similar stock trends, although estimates have high variability. We use equilibrium calculations to determine various fishing mortality reference points. These suggest lower, more conservative, fishing mortality levels than those found in previous analyses. We estimate yield by applying a target fishing mortality to the 1999 estimates of biomass from the catch-age analysis. Current yield recommendations are reduced significantly from previous years. The yield range for rock sole is 600-700 t, while the yield range for English sole is 300-400 t. We synthesize this information to provide advice to managers on harvest levels for the 2001/2002 fishing year.

Résumé

Les auteurs résument l'information biologique sur les stocks de fausse limande et de carlottin anglais du détroit d'Hecate et en analysent les données de prises par âge. Ils se sont servi d'un modèle d'espaces d'états des prises par âge pour reconstituer l'historique des stocks. Les résultats indiquent que le recrutement et la biomasse des deux espèces ont diminué depuis quatre ans. Les recrutements n'ont jamais été aussi faibles pour ces deux espèces, particulièrement en 1998 et en 1999. Les auteurs comparent les biomasses estimées à partir de l'analyse des prises par âge avec celles obtenues par la méthode des aires balayées appliquée aux taux de capture de la pêche commerciale et de relevés scientifiques. Malgré la grande variabilité des estimations, toutes les analyses montrent des évolutions de stocks semblables. Les auteurs ont utilisé des calculs à l'équilibre pour déterminer divers points de référence de la mortalité par pêche, qui semblent indiquer des niveaux de mortalité par pêche moindres que ceux obtenus dans des analyses antérieures. Les auteurs estiment le rendement en appliquant un taux cible de mortalité par pêche aux estimations de biomasse en 1999 provenant de l'analyse des prises par âge. Les recommandations de rendement actuelles sont considérablement réduites par rapport à celles des années antérieures. L'étendue du rendement est de 600 à 700 t pour la fausse limande tandis que celui du carlottin anglais est de 300 à 400 t. Les auteurs synthétisent cette information pour conseiller les gestionnaires sur les niveaux de pêche pour l'année 2001-2002.

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1 Introduction

The groundfish resource in British Columbia (B.C.) increased in importance in the late 1970s with the implementation of Extended Jurisdiction in 1977 and subsequent expansion of the domestic fleet. This prompted the first assessments of groundfish in 1977 (Westrheim 1977). These assessments consisted of a summary of the available information for important species including rock sole (*Lepidopsetta spp*) and English sole (*Parophrys vetulus*). Recommendations for management of these species were not forthcoming until 1979 (Ketchen 1980). Since that time, detailed and interim assessments have been conducted annually including recommendations for catch limitations for these two species. The last detailed assessment was conducted in 1997 (Fargo and Kronlund 1997).

Rock sole and English sole are important components of the traditional trawl fishery in Hecate Strait along with Pacific cod (*Gadus macrocephalus*). Regular sampling of this fishery has resulted in a time series of length and age composition data that extends back to the mid 1940s. The population dynamics of rock sole and English sole populations in Hecate Strait have been studied extensively and estimates of life history characteristics such as natural mortality, growth, and maturity/fecundity are all available for these two species.

The life history of rock sole was first studied in the mid-1940s by Forrester and Thomson (1969), while Ketchen (1956) investigated the life history of English sole. Stocker (1980) conducted the first sequential population analysis for these species. An annual series of trawl surveys (1980-1985) aimed at providing an index of abundance for juvenile rock sole and English sole (Fargo and Westrheim 1987). A second series of trawl surveys began in 1984, with the different goal of collecting data on species interactions in Hecate Strait (Fargo and Tyler 1991). Both surveys took place in 1984, the last juvenile survey occurred in 1985, and subsequently (1986-present) the multispecies survey continued on a roughly biennial basis. The latter series produces catches of juveniles and adults of various flatfish species over the entire Hecate Strait region.

In this document, we summarize biological information and present the results of catch-age analysis for stocks of rock sole and English sole in Hecate Strait. We use a state space catch-age model to reconstruct stock history for both species. The results of the catch-age analysis are compared to those obtained using swept-area expansions of commercial and research survey catch rate data. Yield recommendations are estimated by applying target fishing mortality reference points to the most current estimates of biomass. We synthesize this information to provide advice to managers on harvest levels for the 2001/2002 fishing year.

2 Biology and Life History

2.1 Rock sole

2.1.1 Range and stock structure

The rock sole is an important pleuronectid in the North Pacific. There are three species recognised: *Lepidopsetta mochigarei*, in the Kuril Islands and Sea of Japan, *Lepidopsetta bilineata* which ranges from Baja California to the Bering Sea and (*Lepidopsetta polyxystra*) which ranges from Puget Sound to the extreme southeastern Bering Sea (Orr and Matarese 2000). Research on the life history of *Lepidopsetta spp* has been carried out in British Columbia since the mid-1940s and in Alaskan waters since the early 1960s. Stock delineation work of Ketchen (1982) and Fargo and Westrheim (1987) indicates that the stocks in Hecate Strait constitute a metapopulation. However, these putative units are treated as a single unit for assessment and management.

2.1.2 Niche

Rock sole in Hecate Strait inhabit depths from 5 to 100 m and show a preference for bottom temperatures between 7.5 and 10.5 degrees centigrade (Perry et al. 1994). Adults show little affinity for a particular sediment type, while juveniles prefer coarse sand or gravel substrate. Juveniles feed primarily on mobile prey, such as cumaceans, carideans, and gammarid amphipods. Adults prefer Pacific sandlance (*Ammodytes hexapterus*) and to a lesser extent herring (*Clupea harengus*) (Forrester 1969). Adults also feed on more sedentary invertebrates, such as polychaetes, echiuroids, mollusks, echinoderms, benthic fishes and urochordates. Diet variation results as much from food availability as it does from prey preference. Juveniles are eaten by larger fishes. Cannibalism by adults on larvae and juveniles can be detrimental to populations in Alaska (Wilderbuer and Walters 1999), but this behaviour has not been observed for the Hecate Strait stock.

2.1.3 Growth/lifespan

Rock sole exhibit sexual dimorphism. As juveniles (< 30cm), males and females grow at the same rate. However, after sexual maturity, females grow faster than males, and attain a larger maximum size. The maximum size for male rock sole in port samples over the last 50 years is 47 cm. The maximum size for females over the same period is 56 cm. The maximum weights for males and females are 1490 g and 2010 g, respectively. The growth in weight is also similar among the sexes until maturation. Thereafter the weight gain by females is significantly higher than for males.

Age at 50% maturity is approximately 3 to 4 years for males and 4 to 5 years for females. Age at recruitment to the exploitable population ranges between 4 and 5 years. The maximum age recorded for this species in B.C. is 21 years, although most of the exploited population is less than 12 years of age.

2.1.4 Reproduction/life history

Rock sole are non-intermittent spawners and peak spawning occurs at shallow depths (20-30 m) in March-April (Shvetsov 1979). Interannual variability in the time of peak spawning is relatively low compared to other flatfish species in the north Pacific (Forrester 1969). A 35 cm fish may produce 400,000 eggs per year, whereas a 46 cm fish may produce up to 1,500,000 eggs per year. Rock sole eggs are demersal and adhesive. In Hecate Strait, they incubate for 10 to 15 days prior to hatching. Larvae migrate in the water column from 5-10 m during the day to 30 m at night, most likely following the peak abundance of copepod nauplii. Larvae are transported by wind-driven and tidal currents. The larval pelagic phase lasts for 4 to 6 weeks and metamorphosis takes from 3 to 7 days. The larvae assume their demersal form at about 20-mm in length. Young of the year and one year olds occupy shallower depths (5-20 m) than the adults, while two and three year olds are generally found ir deeper water (20-100m) with the adults. Rock sole occupy separate spawning (winter) and feeding (summer) areas. The main spawning area is off Cumshewa Inlet off the east coast of Moresby Island. They undergo a southerly movement to shallower water in the late winter to spawning grounds. They undertake an easterly post-spawning migration to summer feeding grounds in the central portion of the Strait.

2.1.5 Factors influencing abundance

Past work has suggested that both density-dependent and density-independent factors regulate the abundance of this species. Spawning biomass and ocean temperature at the time of spawning are two significant determinants of abundance. In the past low recruitment has been associated with low spawning biomass and warm ocean temperatures during larval development (Forrester and Thomson 1969, Fargo and McKinnell 1989, Fargo and Wilderbuer in press). Recruitment for these stocks has fluctuated over time with the last significant increase occurring during the late 1980s and early 1990s. Recent work of Fargo and Wilderbuer (2000) indicated that for rock sole, production was impared with stock sizes below 40% of the pristine level.

2.2 English Sole

2.2.1 Range and stock structure

English sole (*Parophrys vetulus*) is found along the Pacific coast of North America from California to Alaska. Along the coast English sole abundance declines with increasing latitude and Hecate Strait is near the northern limit of its commercial abundance. Research on English sole life history has been carried out extensively in the U.S. and Canada over the last 50 years. Results from tagging studies have indicated that there is one population in Hecate Strait (Fargo et al. 1984, Fargo 1999).

2.2.2 Niche

English sole inhabit depths from 5 to 150 m (Fargo 1994) with juveniles preferring shallower depths than adults. The nursery area for young of the year and age 1 fish is located at

shallow depths (0-20m) in the nearshore area off Graham Island (Ketchen 1956, Fargo et al. 1982, Stocker et al. 1981). The species shows a preference for a bottom temperature between 7 and 10 degrees centigrade and adults and juveniles prefer sandy-mud substrate (Perry et al. 1994). Larvae are planktivorous eating different life stages of copepods and other small plankton. Juveniles feed on harpacticoid copepods, gammarid amphipods, cumaceans, mysids, polychaetes, small bivalves, clam siphons, and other benthic invertebrates. Adults feed on a variety of benthic organisms, but primarily polychaetes, amphipods, molluscs, ophiouroids, and crustaceans.

2.2.3 Growth/lifespan

English sole exhibit sexual dimorphism with females attaining a much larger maximum size than males. The maximum size for male English sole from port samples over the last 50 years is 39 cm. The maximum size for females over the same period is about 50 cm. The maximum weights for males and females are 590 g and 1189 g, respectively. Growth of juveniles is similar for both sexes until about age 3 with the onset of sexual maturity at about 30 cm. Thereafter the female growth rate is significantly higher than that of males. Males exhibit very little somatic growth after reaching sexual maturity and devote most of their energy to reproduction. This is likely due to the protracted female spawning season. There is evidence of inter-annual variability in both maturation and growth (Fargo and Sexton 1991, Fargo and Tyler 1994). Although the maximum observed age for the species is 22 years (Chilton and Beamish 1982), fish older than 12 years are seldom seen in samples collected from the commercial fishery.

2.2.4 Reproduction/life history

English sole are non-intermittent spawners and the spawning period for Hecate Strait English sole is protracted, as is the case for stocks in U.S. waters. The species demonstrates considerable phenotypic plasticity in reproduction likely an adaptation to the oceanographic conditions its pelagic eggs and larvae are exposed to. Spawning occurs from September to March with peak spawning usually occurring during October-November (Fargo and Tyler 1994, Boehlert and Mundy 1987, Kruse and Tyler 1983, Kruse and Tyler 1989). Larger, older fish spawn in the late fall and younger fish ripen more slowly and spawn in the spring (Foucher et al. 1989, Fargo and Sexton 1991). Hatching occurs in 6 to 10 days following spawning depending on the temperature and salinity of the surrounding seawater. English sole eggs are euryhaline and both temperature and salinity influence hatching and larval development. The pelagic larval phase lasts 6 to 10 weeks (Forrester 1969), during which time the larvae are distributed from the surface to depths of 20 m and drift with the prevailing currents in the Strait. Metamorphosis begins around 6 to 8 weeks following hatching and occurs over a 5 to 10 day period (Boehlert and Mundy 1987). Settlement occurs within 3-9 days after metamorphosis. As 2 and 3 year olds English sole gradually occupy deeper depths and by the time they reach 4 years of age, they mix fully with the adult portion of the stock.

2.2.5 Factors influencing abundance

English sole abundance and recruitment exhibit decadal oscillations thought to be the result of changes in the environment as well as changes in the stock spawning biomass (Fargo 1994). High ocean transport is associated with low recruitment and year-class production declines rapidly with the spawning biomass below 30% of the pristine stock size (Fargo 1994). Physical oceanographic processes occurring during the egg and larval stages (Ketchen 1956, Alderdice and Forrester 1969, Westrheim 1977, Fargo 1994) are important determinants of year-class success for this stock as is spawning biomass (Fargo 1994).

3 Data Sources

3.1 Commercial trawl data

The Department of Fisheries and Oceans has maintained records of groundfish catch and effort data from 1954 to 1995 using a combination of skipper interviews, vessel logbooks, landings records (sales slips or validation records) and observations at the waterfront. These data are archived in a database called GFCATCH (Leaman and Hamer 1985), the history of which has recently been described in detail by Rutherford (1999).

Skipper interviews and logbooks provided information on fishing areas and amount of effort, however, the catch for each species was estimated. Species composition was usually limited to the dominant species retained in the catch (Rutherford 1999). Skipper interview and logbook data were transcribed into a trip report by DFO staff. Sales slips or validation records provided accurate weights of species landed, but little information on fishing location or effort. If an offload was observed, information might be gathered that supplemented or superceded logbooks and landing records. For example, errors in species identification might be corrected. The "best" estimate of catch required synthesis of all data sources. Typically, the actual weights from landings were used to adjust the trip reports by prorating the landed weights using fishing location and catch information recorded at sea (Leaman and Hamer 1985).

For data collected during the period 1996 to 1999 we used a mirror of the Fortran implementation of GFCATCH (Leaman and Hamer 1985) implemented in Microsoft SQL Server 7.0. This GFCatch (SQL) database resides on the PacStad server at the Pacific Biological Station. A Microsoft Access shell (GFCatch.MDB) was used to extract the catch and effort data used in this assessment. Small discrepancies in the catch history between this assessment and previous assessments are a result of corrections to the historical catch.

3.2 Commercial trawl observer data 1996-2000: PacHarv database

A mandatory at-sea observer program was implemented for most Option A and some Option B trawl vessels in 1996. This includes some 90% of the trawl fleet. The observers provide information on catch locations, bridge log data and species composition (by weight). Observers also collect biological data for selected species. A relational database, *PacHarvest*, was developed by the slope rockfish assessment team using Microsoft Server 7.0 (Schnute et al.

1999). The database is located on the Windows NT server PacStad at the Pacific Biological Station, Nanaimo, B.C. Documentation and database shells for connecting to *PacHarvest* can be found on the DFO Intranet at http://pacstad/pacharvdb/Default.htm. Further details can be found on the website and in Schnute et al. (1999).

3.3 Dockside validation

Since 1996 every trawler unloading is monitored at the port of landing. The dockside validator estimates the species composition of the landing by weight. This information is used together with observer at-sea information to resolve the species composition (by weight) of the catch. Dockside validation data for trawl is contained in the database tables *B5_Validation_Headers* and *B6_Validation Species* of the *PacHarv* database described above.

3.4 U.S. landing statistics

The commercial trawl fishery in Hecate Strait involved both Canadian and U.S. vessels from 1956 to 1977. In 1977 Canada declared extended jurisdiction over offshore resources to 200 miles. Vessels in the U.S. fleet were no longer permitted to fish in Canadian waters after that time. Although rock sole was a component in the catches of U.S. vessels, it was mainly discarded due to weak markets for this species in the U.S..

3.5 Hecate Strait assemblage survey

In 1984 a multispecies trawl survey was initiated in Hecate Strait (Fargo and Tyler 1991). This work was carried out as part of the Hecate Strait Project (Fargo 1986, Fargo 1989) with an objective to develop an ecological basis for mixed species stock assessment. The survey provided synoptic data that allowed the mapping of fish assemblages available to bottom trawls in that region. Although the Hecate Strait Project work halted in 1993, the multispecies assemblage survey was continued (Hand et al. 1994, Workman et al. 1996, Wilson et al. 1991). The survey now provides data on the abundance and distribution of rock sole and English sole in the region. The survey data has also been used to document the spatial and temporal changes in species composition in Hecate Strait. The fishing gear used on the survey, a Yankee 36 bottom trawl, has remained the same since its inception. The net is equipped with a small-mesh codend liner to ensure sampling of all size/age groups.

The survey employed a systematic depth stratified design. A grid of 10 X 10 nm blocks was superimposed on a chart of the region. Sampling stations within each block were allocated for each 20 m depth interval. The selection of a station within a stratum was made by the fishing master who searched each stratum for trawlable bottom. At the end of each tow, the species composition of the catch by weight was determined and length measurements were made for all species in the catch. Exceptions to this procedure occurred when the catch was >3000 lbs. whereupon a random subsample was taken for the collection of biological data.

3.6 Biological data

Biological samples containing length, sex, maturity, and ageing information have been collected from the trawl fishery in Hecate Strait continuously since the mid 1940s. Listings of the number of observations for biological characteristics for rock and English sole are summarized by year in Table 1 and Table 2, respectively. These samples were collected by port samplers at the port-of-landing. Sample sizes were large during the early years of data collection compared to the later years. The stage of maturity was determined macroscopically according to a maturity atlas including seven stages, two immature and five mature. There is more information on length/sex in these samples than on maturity and age. This was due to the time constraint of sampling in fish plants.

Biological samples have also been collected from numerous research cruises including the previously mentioned Hecate Strait assemblage survey. In the early years of the survey attention was devoted to sampling every species in the catch to provide data for multispecies stock assessment work. This permitted the collection of size composition data only. Since the 1996 survey, however, biological samples for important commercial species have included information on length, sex, stage of maturity and ageing structures. The result of complete sampling of the size spectrum of individual species is the ability to compile a CPUE index for juveniles and adults. Similarly, the age composition data from the survey can be used to highlight bias in the sampling of commercial catches.

4 Landing statistics

4.1 Rock sole

Landing statistics for rock sole are presented in Table 3. Rock sole landings exhibit cyclic fluctuations although these cycles are less apparent prior to 1965 . Catches in excess of 2000 t have occurred only twice, once in the mid 1960s and once in the early 1990s. The peak in the mid 1960s corresponded to the discovery of the spawning concentration of rock sole in the southwestern Strait. There was an abrupt decline in landings between the late 1960s and the mid 1980s. This occurred for two reasons: 1) the spawning stock was probably fished down by that time and 2) this was a period of prolonged poor recruitment. In the early 1990s landings increased to the highest level on record due to strong recruitment. Since 1995 landings, effort and CPUE have declined continuously. However, CPUE has not been used as an abundance index in this assessment due to regulatory and market effects. Richards and Schnute (1986) showed that CPUE was a poor abundance index for single species caught in a multispecies fishery as is the case for both rock sole and English sole in Hecate Strait. The 400 tonnes landed in 1999 is well below the long-term average of 1055 tonnes. Similarly, the 1999 effort of 1709 h is also below the long term average of 1995 h.

4.2 English sole

Landing statistics for English sole are presented in Table 4. The cyclic fluctuations in the landings are less apparent for English sole than rock sole. After the removal of nearly 5000

tonnes between 1950 and 1952 landings declined to about 600 t and have fluctuated around this level until the early 1990s when they increased to 1200 tonnes. Since that time landings have declined steadily and in 1999 amounted to around 400 tonnes. Only the mid to late 1940s have lower landings. As in the case of rock sole, detailed landings data prior to 1954 are not available so we have used the summary of Ketchen (1980) for the mid 1940s to mid 1950s. The implementation of observer coverage in 1996 and the IVQ program in 1997 has perturbed the comparability of the data for recent years with the historical data. Since 1995 landings, effort and CPUE show declining trends. However, the commercial CPUE index has been discounted for the same reasons given for rock sole in section 4.1. The 368 tonnes landed in 1999 is well below the long term average of 758 tonnes, while effort in 1999, 2178 h, is well above the long term average of 1235 h.

5 Management History

Management of the fishery for rock and English soles has involved the implementation of annual quotas and vessel trip limits (Table 5). Prior to 1985 there were no catch or trip limits for these species. A 14 tonne trip limit was established for rock sole from 1985 to 1992. In 1993 the trip limit was reduced to 9 tonnes. Beginning in 1994, an annual quota was used to limit catches and has ranged from 1000 t to 1500 t since that time. Since 1990, a quota ranging from 700 to 1000 t has been used to limit the catches of English sole in Hecate Strait. Also, approximately 40% of the area in the shallows on the western side of the Strait has been closed to trawling since 1996 because of Dungeness crab (*Cancer magister*) conservation concerns. This encompasses about half of the fishing grounds for rock sole.

Pacific groundfish have a complex management history, with a variety of historical regulations. The assessment team has initiated work on an Access database to capture some of this historical complexity.

6 Estimation of life history, and fishing reference points

6.1 Length weight relationship

Parameters for the length weight relationship

(1) $$\ln W_i = a + b \ln L_i \quad , (1 \le i \le n)$$

where W_i is the weight (kg) and L_i is the length (cm) of fish i, were determined from pooled port samples for 1956 to 1999 and from research surveys conducted between 1984 and 1998. Rock sole males rarely reach a size of 40 cm while females commonly reach a size of 50 cm (Figure 1). Weight at age is similar among the sexes until around 30 cm (4 years), the time of sexual maturation. Thereafter the females surpass the males in weight at length. The situation is the same for English sole (Figure 2).

6.2 Length at age relationships

Mean length at age was determined for each year from annual port samples. Mean weight at age was also determined for each year using the length-weight relationship and length-age data for each year for the catch-age analysis.

Von Bertalanffy growth curves were fit to data for both species (Figures 3, 4). Growth in length for rock sole males slows markedly after about age five while females continue to grow in length throughout their life. Growth in length for English males slows significantly after age four and growth in length is not apparent after age six. Female English sole continue to grow in length throughout their lifetime (20 years).

6.3 Maturity

We estimated length at maturity for the catch-age model using data obtained from samples from research cruises and the commercial fishery. Stage of maturity was determined macroscopically and fish were partitioned into one of seven maturity stages (Workman et al. 1996), two immature and five mature. Fish at stages one and two were treated as immature and fish at stages 3-7 were treated as mature. Length-maturity data were obtained from pooling the data to aquire an adequate sample size. Maturity ogives were fit to these data using a simple logistic regression (Hosmer and Lemeshowe 1989), where the probability of a fish being mature at a given length L, P_L, is a function of the length, L, and the regression coefficients β_0 and β_1.

$$P_L = \frac{e^{\beta_0+\beta_1 L}}{1+e^{\beta_0+\beta_1 L}} \qquad (2)$$

Both species begin to mature at a size of about 30 cm but the rate of maturity at length is different among the sexes and among the two species. L_{100}, the length at which 100% of the fish are mature, is 39 cm for male rock sole and 42 cm for females (Figure 5). The rate of maturity is slightly higher for rock sole males than for females. The rate of maturity for English sole is very different among the sexes. Although both sexes begin to mature at a size of 30 cm the maturation rate is much faster for males than for females. The length at which 100% of the fish are mature ,L_{100}, occurs at a size of about 35 cm for males compared to 42 cm for females (Figure 6).

6.4 Natural mortality

Estimates of the natural mortality rate for rock sole , M, are available from Forrester and Thomson (1969), 0.26 for females and 0.53 for males, Stocker (1980) 0.15 for females and Fargo (1999), 0.20 for females. The estimates of Forrester and Thomson are biased high because they utilised age determinations from otolith surfaces which truncate the lifespan of the species. The estimate of Stocker for females was derived using only a few year's data. The estimate of 0.2 for females used by Fargo (1999) is probably the most reasonable because it corresponds with the life span of the species. It is also close to the value, 0.18, used in stock assessments for this species in Alaska (Wilderbuer and Walters 1999).

Estimates of the natural mortality rate for English sole are available from the work of Ketchen (1956) and Fargo (1999). Ketchen estimated the natural mortality rate to be 0.25 for females and 0.35 for males. However, Ketchen was using readings from otolith surfaces to determine M. The estimate of 0.2 is more realistic given the lifspan of the species. It is also the estimate used in other stock assessments of other flatfish species along the Pacific coast (Wilderbuer and Walters 1999, Turnock et al. 1994, Turnock et al. 1995).

Thus the plausible range for natural mortality, M, for both species is 0.18-0.30 (Fargo 1995, Fargo and Wilderbuer 1999 Wilderbuer 1990 and Demory 1988). To shed more light on this we refer to the work of Pauly (1980). He described a multiple regression relationship between M and life history characteristics and temperature regime of 175 fish stocks. He found that M varied linearly with species asymptotic length L_∞, the growth coefficient K, and mean annual ocean temperature T

(3) $$\log M = 0.065 - 0.287 \log L_\infty + 0.604 \log K + 0.513 \log T .$$

Table 6 shows the results from this analysis. Estimates from Pauly's method are well above the range used for Pacific coast stock assessments and appear inconsistent with the longevity of these two species. However, many of species that Pauly examined were warm water species and this may have biased the results of his regression applied to cold water species. We include them only for documentation of this method in context of these two species. We do not use these estimates in these assessments.

6.5 Sex ratio in the commercial fishery

Sex ratio by weight was determined from port sample data for each year and the length-weight relationship in equation (1) for rock sole (Table 7) and English sole (Table 8). The weight of females greatly exceeds that of males for both species in samples taken from the commercial fishery. Rock sole males made up from 8% to 36% (mean=18%) of the weight of the samples collected from the commercial fishery between 1945 and 2000 (Table 7). Rock sole males made up a higher percentage of the samples collected by weight during the 1946 to 1956 period than for any other period. There was no minimum size limit during that time. Since the imposition of a mesh regulation in 1996 the percentage of males by weight in the samples is slightly lower than the longterm average (mean=14%).

English sole males made up 3% to 50% of the weight in samples taken from the commercial fishery between 1945 and 2000 (Table 8). The average weight of males in samples taken during that period was 22%. English sole males made up a higher percentage of the weight in the samples taken during the 1944 to 1952 period than for any other period (mean=43%). However, there was no minimum size limit at that time. Since the imposition of a mesh regulation in 1996 the percentage is of males by weight in samples is about half the longterm average (mean=10%). Estimating gear selectivity is confounded by the fact that over time fish plants have requested fishermen to sort to different sizes. This phenomena is illustrated in the 1980 sample weight for English sole males. In that year plants asked fishermen to sort catches to

a minimum size of 30 cm. This resulted in a significant increase in the sample weight for males in that year compared to other years.

6.6 Sex ratio in the Hecate Strait survey

The sex ratio for both species was not as biased toward females in samples from the surveys as it was in samples from the fishery. Female English sole and rock sole made up 56% and 59%, respectively, of the numbers in samples from the Hecate Strait surveys. They made up 63 % and 61 % by weight. The disparity of the sex ratios on the surveys compared to the commercial fishery was due to the fact that the fishing gear used is non-selective for flatfish species and furthermore the samples from the trawl survey contain a high proportion of juveniles. The weights at length of juveniles are nearly the same for both sexes for both species.

6.7 Equilibrium reference points

Schnute et al. (1999) describe an equilibrium fishery model used to produce the reference points listed in Table 9. Our appendix A2 provides a complete description of their model parameters and equations. We scale our analyses to a fixed carrying capacity $B_0 = 10$ kt (kilo-tonnes, or thousands of tonnes). The model includes a flexible stock-recruitment function with a shape parameter γ, where various choices γ give the historical formulations of Beverton-Holt ($\gamma = -1$), Ricker ($\gamma = 0$), and Schaefer ($\gamma = 1$). A death rate parameter

$$\delta = 1 - e^{-M}$$

corresponds to the natural mortality M.

The ratio $\rho = R/S$ of recruits R to spawner biomass S represents a measure of productivity. Stocks theoretically become more productive at smaller stock sizes; thus, ρ increases as S decreases. Pristine conditions give a biomass B_0 and a corresponding productivity ρ_0. As abundance declines to zero, the productivity approaches a maximum value ρ_{max}, and the ratio

$$\phi = \frac{\rho_{max}}{\rho_0}$$

gives a measure of the stock's potential increase in productivity from pristine conditions. Our analyses use the rather conservative estimate $\phi = 5$ adopted by Walters and Bonfil (1999) and Schnute et al. (1999).

Table 9 presents calculations for both species with two recruitment curves (Beverton-Holt and Ricker; $\gamma = -1$ and $\gamma = 0$) and two levels of natural mortality M (0.2 and 0.3), based on the choices $B_0 = 10$ kt and $\phi = 5$ discussed above. All remaining parameters come from the growth and weight analyses presented earlier, where we use data for females only.

Figures 7 and 8 show corresponding diagrams for these reference point calculations, although only for the Ricker curve. With $M = 0.2$, Table 9 indicates that the fishing mortality F^* corresponding to maximum sustainable yield (MSY) lies in the range 0.13-0.17 for both species. These values are distinctly lower than a variety of reference levels discussed in last year's assessment (Fargo et al. 1999, FAO 1995), partly due to a difference in the underlying rationale. Reference points from last year's assessments are summarized in the following table:

Reference Point	Criterion	Rock Sole	English Sole
F_{high}	S/R	0.63	0.50
F_{max}	C/R	0.57	0.83
F_{med}	S/R	0.37	0.28
$F_{0.1}$	C/R	0.22	0.25
F_{low}	S/R	0.16	0.11

The 'criterion' column in this table refers to the prototype curve used to define the reference point, as illustrated for our analyses in Figs. 7 and 8.

7 Catch-age model

The population history of stocks of rock sole and English sole in Hecate Strait was reconstructed from the mid-1940s to 1999. The catch-age model used for the reconstruction is a derivation of the state space model described by Schnute and Richards (1995). All required model notation and a complete model definition are provided in Appendix A (Tables A.1-A.4). The model reconstructs the population history from known controls and observations. In this context, the catch acts as a known control on the population dynamics. Observations including proportions at age in the catch and stock abundance indices derived from commercial and/or research survey catch per unit effort describe the current state of the system. The model relates the observations, measured with errors, to unknown numbers of fish in the population. Table A.2 presents a deterministic version of the model, and stochasticity is introduced in Table A.3. We introduce four potential sources of error: (1) autoregressive log-normal process error among the recruitments, (2) log-normal process error in the survivals, (3) log-normal measurement error in the stock index, and (4) multivariate logistic measurement error in the observed age proportions. Table A.4 contains definitions of model residuals and a statement of the components of the likelihood function for the model. Process error in the survivals is ignored in the analysis. A known variance ratio between recruitment process error and stock index measurement error is assumed in order to avoid singularities in the maximum likelihood function. Tables A.5 and A.6 state the model used in catch at age assessments of rock sole and English sole prior to this document (e.g. Fargo 1999) for completeness.

Data were pre-processed prior to catch-age analysis to render a female only model as described below. Specific manipulations were applied to the age data, commercial catch, commercial CPUE stock index, and research survey stock index.

7.1 Commercial landings and catch rate data

The commercial landings for each year have been multiplied by an estimate of the proportion of females, π_t, by weight in the catch computed from port samples (Tables 7 and 8). Similarly, the commercial stock abundance index (median CPUE) was multiplied by the estimates of π_t for all years of available data. However, this index was subsequently dropped from the analysis as described Section 8.

7.2 Selectivity

Recruitment to the fishery is not knife-edged and fish of both species are not fully recruited until about 5 years of age. Prior to this assessment, fishery selectivity was allowed by vary with age class, but was time invariant. However, a mesh regulation mandated in 1996 established a minimum codend mesh size of 6 inches, an increase from the 4.5 inch mesh in use before that time. The objective of the increased mesh size was to allow greater escapement of small fish. Mesh selection studies (Forrester and Thomson 1969, Stanley and Davenport 1982) indicated that a 6 inch codend is 50% selective for rock sole of 34 cm (age 3 and older) while a 4.5 inch codend was 50% selective for rock sole of 25 cm (age 2 and older). A 6 inch codend is 50% selective for English sole of 35 cm (age 3 and older) while a 4.5 inch codend was 50% selective for English sole of 30 cm (age 2 and older). However, fish less than 35 cm are seldom seen in samples from the commercial fishery because of the low recovery rate for fillets from small fish. Thus the minimum size/age in the landings for both species is market-driven.

Consequently, the two parameter selectivity function used in previous assessments (Fargo 1998) was extended to allow the proportion of fish selected at the first age class (age 4) to vary between the pre-1996 and 1996 to 1999 periods (Appendix A). A likelihood ratio test of the hypothesis $H_0 : \Delta = 0$ can be computed to determine whether selectivity of the first age class varied between the two periods, presumably as a result of the change in minimum mesh size.

7.3 Proportions at age

The age composition time series for both of these species spans more than half a century. The trawl fishery at Two Peaks and Butterworth grounds in northern Hecate Strait is the oldest on the coast. Landings of rock sole and English sole from this area amount to ~71% of the total landings for these species in Hecate Strait. This area is a prime feeding area for adults of both species. Biological samples have been collected continuously from this fishery, although vessel log information is only available since 1954. This analysis relies on age composition data from the commercial fishery observer samples and catch rate and biological data from research surveys. Samples collected from the fishery at Two Peaks-Butterworth area were used as input for the catch-age model. They were pooled across months to obtain an adequate sample size for analysis. This increases the amount of variation in length at age and weight at age due to seasonal differences but avoids the bias of selecting data from different monthly periods for each year. The data used provide the longest directly comparable time series for analysis. We used a range of ages 4 to 12+ with the last age group representing fish aged 12 years or older. Three-year-olds are not fully recruited (they are negligible in commercial landings) and fish 12 and older were grouped together because of differences in the ageing technique. Otolith surface

readings (1945-72) under-estimate the ages of older fish (beginning at age 12) compared to readings made from otolith burnt cross-sections (1973-99). The catch-age data covers the period from 1945 to 1999 for rock sole and from 1944 to 1999 for English sole.

7.4 Stock indices

Catch rate data from the Hecate Strait assemblage survey were selected to give an approximate female stock index for tuning the model. This index represents female fish age 4 and older, since four year olds are the minimum age considered in the analysis. We used the length frequency data for each survey tow to partition fish into two groups, juveniles and adults, based on size threshold of 30 cm. At 30 cm, only 3% of the English sole males were mature while 1% of the females were mature. For rock sole 5% of the males were mature at 30 cm while about 2% of females were mature. For both species, this composition above this size threshold includes fish that are age 4, *i.e.* those that are recruiting to the fishery.

8 Model Evaluation

We present the results of four different model configurations for rock sole (Table 10) and English sole (Table 11), based on various choices for the natural mortality M and the model selectivity parameter Δ (Section 7.2). We examined other scenarios that tested various values of ρ, or included a commercial CPUE index. These either generated implausible results or produced no additional information useful in formulating advice. All configurations listed in Tables 10 and 11 used the Hecate Strait survey CPUE series as the stock index. We rejected the use of commercial CPUE because of problems with standardization, possible bias due to hyperstability, and the possible cumulative effects of regulations on the latter portion of the times series (Quinn 1985, Richards and Schnute 1986, Richards, L.J. and J.T. Schnute 1992).

8.1 Rock sole

The modified selectivity curve had little impact on the results as indicated by the small change in log likelihood values between Case 1 and Case 2 (Table 10). The terminal biomass estimates were slightly higher for the Case 1, which allowed for a different selectivity of the first age class. We expected that adjusting for a presumed change in selectivity over time would produce higher population estimates for the most recent years. Despite this, we allowed time variant selectivity (Δ free to be estimated) in subsequent model runs.

To investigate this result further, we examined the size composition data obtained the trawl observers and from the Hecate Strait assemblage survey (Figure 9). The size composition data reported by observers between 1996 and 1999 were grouped into unsorted and sorted ('kept') catch. The kept catch reflects fish retained by the trawl fishermen. Inspection of Figure 9 reveals that despite the mesh regulation a proportion of the catch is still being discarded (compare the size distributions relative to the 300 mm reference line). The size composition for the year 2000 Hecate Strait survey included all sizes available to trawl gear, and includes juveniles that are not retained by the commercial fishery. From this, the mesh regulation appears to have reduced the amount of discards of juvenile sole but has not eliminated them. There are

several explanations for this result, including 'packing' of the codend with large catches, which prevents escape of undersize fish. In addition spatial variation in the proportion of juveniles in Hecate Strait may act to change the level of discards, so that the catch of undersize fish by commercial vessels may reflect the area fished.

Model sensitivity to changing values for ρ has been examined in previous assessments (Fargo and Kronlund 1997). The relative amount of total recruitment and stock index variation assigned to σ_t^2 or τ_t^2 is varied by changing ρ. Unless ρ was extremely high (>0.99) or extremely low (<0.10) there was little impact on the model results. For example, changing the value of ρ from 0.7 to 0.5 had no significant effect on the time trend of either the biomass or recruitment series for either species.

We also examined the sensitivity of the model to different values of M (0.2, 0.3) with ρ=0.7 (Table 10, Cases 2 and 3). Small changes in the negative log likelihood value were observed, with the expected increase in terminal biomass B_{1999} with M=0.3. When M was allowed to be free (Case 4), the solution indicated an estimate of M=0.246.

We selected Case 1 as the best reconstruction of the rock sole population and based yield recommendations on the estimated terminal biomass (Figure 10). Recruitment, exploitable biomass, and spawning biomass trajectories from the model are presented in Figure 11. Observed proportions at age were compared to predicted proportions at age (Figure 12) to determine how successfully the model reproduced strong year cohorts. Model residuals for the age proportions were examined for pathologies (Figure 13). There were no obvious trends in the stock index residuals over time. However, there often were negative residuals for the plus group in the early years of the data series, possibly a result of the change in age determination methods, although the adoption of an age 12 accumulator group should have minimized this effect.

Model results suggested the exploitable female biomass of this stock in the late 1940s was low, about 1000 t (Figure 11). Biomass increased to 4000 t by 1966 and then declined to 2000 t by 1980. Between 1980 and 1995, the exploitable biomass for this stock increased to the highest level recorded in the last 50 years, nearly 6000 t. Biomass has declined since that time. The estimate of exploitable female biomass in 1999, and associated 95% confidence interval, was 3031t (1741t, 5277t). Female rock sole accounted for an average of 0.817 of the total sample weights over time (Table 7). Applying this factor to the estimate of exploitable female biomass resulted in an estimate of total exploitable biomass in 1999 of 3710 t, close to the longterm average.

The recruitment trend is synchronous with that for exploitable biomass (Figure 11). Recruitment increased to the highest level on record in 1992, but has declined steadily since that time. This decline is in agreement with an index of recruitment for juveniles (<30cm fork length) derived from the Hecate Strait assemblage survey (Figure 14). Over the last three years recruitment has been the lowest on record. Thus these results indicate that biomass is now being fished down with minimal replacement. The model estimates of annual fishing mortality over time are presented in Figure 10. Fishing mortality for the stock in 1999 was estimated to be 0.15.

Approximations to a marginal Bayes posterior probability distribution were computed for the terminal fishing mortality rate, F_{1999} and the (log) terminal female exploitable biomass B_{1999} using the model corresponding to Case 2 for both species (Tables 10 and 11). In addition, the marginal posterior for the natural mortality rate, M, was computed for Case 4 of both species. Computations were performed using the "profile likelihood" capabilities of AD Model Builder (Otter Research Ltd., P.O. Box 2040, Sidney, B.C.).

Probability density functions of the parameters (F_{1999}, B_{1999}, M) for rock sole appear in Figure 15. The vertical dotted line on the left side of each panel shows the point where the probability is 0.9 that the value is greater than the indicated value. Similarly, the vertical dotted line on the right side of each panel locates the point where the probability is 0.9 that the value is smaller than the indicated value.

Values of the (log) exploitable female biomass for rock sole at the two 0.9 probability points are 0.803 (2,332 t) and 1.593 (4,917 t). The approximate posterior density of M is consistent with what is expected given life history considerations.

8.2 English sole

In contrast to the results for rock sole, the model fit for English sole improved modestly due to the inclusion of the time variant selectivity function (Table 11, Case 1 and 2) with slightly higher estimates of terminal biomass (1,911 versus 1,714 tonnes). Time variant selectivity was retained for subsequent model runs. Model sensitivity to changing values of ρ was similar to that reported for rock sole. As for rock sole, we examined the sensitivity of the model to changes in the assumed natural mortality rate (Case 2 and Case 3) by fixing M at 0.2 and 0.3 with $\rho = 0.7$ (Table 11, Cases 1 and 2). The negative log-likelihood decreased by a significant amount from Case 1 to Case 2, with the expected increase in terminal exploitable biomass (1,911 to 2,679 t). When M was allowed to be free (Case 4), the solution indicated an estimate of M=0.48. This value is improbable given what is known about English sole life history (section 6.4).

We chose Case 1 as the appropriate reconstruction to develop management advice (Figure 16). Recruitment, exploitable female biomass and spawning biomass trajectories from the model are presented in Figure 17. Observed proportions at age were compared to predicted proportion at age (Figure 18) to determine how successfully the model reproduced strong year cohorts. Model residuals for the age proportions (Figure19) were examined for pathologies.

The reconstruction (Figure 17) suggested that between the mid 1940s and the mid 1970s the biomass of this stock fluctuated without much trend (mean ~ 2000 t). From the mid 1980s to the mid 1990s, biomass increased to about 3500 t. The estimate of the exploitable biomass of females in 1999 was 1911 t (1175, 3105)t. Female English sole accounted for an average of 0.777 of the total sample weights over time (Table 8). Applying this factor to the estimate of

exploitable female biomass resulted in an estimate of total exploitable biomass in 1999 of 2459 t, close to the longterm average.

The trend in recruitment is synchronous with that for exploitable female biomass. Recruitments in 1992 and 1993 were the highest on record. Between 1993 and 1999 recruitment declined dramatically. This decline is in agreement with an index of recruitment for juveniles (<30cm fork length) derived from the Hecate Strait assemblage survey. Recruitment in 1998 was very low, although it appeared to increase slightly in 1999. A significant increase in stock biomass occurred in the early 1990s due to strong year-classes produced in the late 1980s. However, by the late 1990s significant declines in both recruitment and biomass had occurred. English sole adult and juvenile CPUEs from research trawl surveys conducted in Hecate Strait declined over the same period (Fargo 1998) (Figure 20). The model estimates of annual fishing mortality over time are presented in Figure 16. Estimated fishing mortality for the stock in 1999 was 0.19.

Probability density functions of the parameters (F_{1999}, B_{1999}, M) for English sole appear in Figure 15. As in the discussion of rock sole, a vertical dotted line on the left side of each panel shows the point where the probability is 0.9 that the value is greater than the indicated value. Similarly, the vertical dotted line on the right side of each panel locates the point where the probability is 0.9 that the value is smaller than the indicated value. For example, the probability is 0.9 that the terminal fishing mortality for English sole is greater than 0.143. On the upper tail of the density, the probability is 0.9 that the terminal fishing mortality is less than 0.265 for English sole.

Values of the (log) exploitable female biomass for English sole are 0.340 (1,405 t) and 0.986 (2,679 t). The approximate posterior density of M for English sole indicates a mode at about 0.48, accompanied by a second higher mode above 0.65. This suggests that the model converged to a local minimum.

9 Biomass Estimation using Spatial Data

9.1 Walters and Bonfil (1999)

Walters and Bonfil (1999) presented an alternative assessment of B.C. groundfish stocks based on the following suite of methodologies. Their analysis included assessments of rock sole and English sole coastwide and by fishing grounds. Current stock size was estimated using two methods. First, an *ad hoc* spatial interpolation of commercial catch rates from trawl observer data was performed, followed by the application of the swept-area method to produce biomass estimates. Second, the results of a Bayesian estimation procedure were presented in terms of the ratio of current (1996) biomass to unfished biomass. This procedure used a delay-difference model for qualified CPUE for 1980 to 1996, with various assumptions regarding unfished biomass, to reconstruct the biomass trajectory for each stock over time. Minimum biomass estimates (t) for 1996 listed in Table 12 were extracted from Table 3 of Walters and Bonfil 1999). These estimates, were computed using swept-area expansion of interpolated commercial CPUE, and represent the estimates from grounds 1 and 2 of Walters and Bonfil (1999, Fig. 4).

The grounds corresponded to frequently trawled areas in Hecate Strait north of Moresby Gully. Also shown in Table 12 are the ratios of 1996 biomass (t) to unfished biomass (t), B_{1996}/B_0, for each of the grounds. Ratios less than 0.5 represent 'overfished stocks' in the analysis of Walters and Bonfil (1999, Table 6). Finally, coastwide estimates of "minimum" maximum sustained yield (MSY) and "most probable" MSY from the Bayesian single-stock assessment (Walters and Bonfil 1999, their Table 7) are included in Table 12 since the majority of the coastwide catch of rock and English soles is comes from Hecate Strait.

Flatfish species like rock and English soles are more amenable to the techniques of Walters and Bonfil (1999) compared to aggregating species. Flatfish inhabit primarily trawlable grounds with little depth gradient relative to the high relief rocky habitat of species like the rockfishes and lingcod. They are uniformly distributed over the grounds as well. However,, targeting (or avoidance) cannot be conducted acoustically. The swept-area method assumed that fishing was random within 1 nm blocks, and that the CPUE of fished blocks was representative of adjacent unfished blocks. In the case of the Bayesian analysis, the comparability of the commercial CPUE series may be suspect because of the accumulation of management tactics (increasingly restrictive trip limits, TACs) over the early 1990s. However, our intent is not to discredit the results of the analysis, but merely to point out that as with any analysis, violations of the model assumptions may occur.

9.2 Schnute and Haigh (2000)

Schnute and Haigh (2000, Can. Stock Assess. Res. Doc. 2000/155) describe swept-area expansion of catch rate data to compute biomass estimates for selected groundfish species in British Columbia waters. Their report provides a complete description of data sources, notation, and model definitions. Their analysis give estimates of biomass beginning in 1994 for Hecate Strait rock sole and English sole, based on both commercial and research survey data. They examine two extreme perspectives on available habitat: (1) fish occur only where they are caught, and (2) fish occur throughout the available area within a depth stratum. The former area is computed by summing all the 1 km^2 blocks in which tows that capture a given species have been observed. The latter area comes from a bathymetric database (Schnute et al. 1999, section 3.6) that records a bottom depth for each 1 km by 1 km block on the B.C. coast. For both flatfish species, the biomass estimator is depth stratified by 40 m intervals ranging from 40 m to 240 m depth. However, due to an observed fish density that is low or zero for depth strata below about 160 m, little contribution to the total biomass comes from those depths.

Estimated habitat area and biomass for rock sole and English sole are shown in Table 13. The various estimates reflect commercial and survey data sources, as well as the two assumptions about available habitat area. A superscript asterisk denotes the lower estimates obtained by using only locations of the species known from the fishery. All estimates are computed by trimming a proportion p of the values from the low and high end of the ordered fish densities prior to multiplying by habitat area, *i.e.,* they are robust to outliers. Mean biomass estimates B and B^* (1996-1999) come from commercial catch rate data (Schnute and Haigh 2000, their Table 5). They also use bootstrap calculations to estimate uncertainty, as portrayed in their quarterly biomass estimates from commercial data (Schnute and Haigh 2000, their Figs. 2e and 2f). Series for both sole species suggest a decline in estimated biomass at about the first

quarter of 1996, which is coincident with significant changes in the management regime such as the placement of observers on trawl vessels, and eventual adoption of IVQs in 1997.

For both species, the estimates B^* (Table 13) are clearly minimum values since both are not much different than current annual catches, or from the mean historical catch. The estimates B are optimistic relative to our catch-age model results for the same period, but are within a factor of 2-4 of estimates in the historical reconstructions. Table 13 also includes annual biomass estimates for 1998 through 2000 (first two quarters only). The numbers in brackets following each estimate indicate the 2.5% and 97.5% quantiles of a bootstrap sample of size 300. These estimates are based on all available habitat area, and represent the mean of the quarterly estimates.

Figure 21 (reproduced from Schnute and Haigh 2000, their Fig. 4) shows biomass estimates derived from the Hecate Strait assemblage survey data. For each survey year, boxplots describe the distribution of 300 bootstrap estimates, based on 10 percent trimmed mean density estimates from the catch of adult (>30cm) flatfish. A circle within each boxplot indicates the corresponding biomass estimate. The time trends are similar to those exhibited by the CPUE index used in the catch-age analysis, which is not surprising given they are computed from the same data. Differences between the biomass and CPUE indices can be attributed to the area-weighting scheme and use of the 10 percent trimmed mean for the biomass estimates. Biomass estimates for the 1998 and 2000 assemblage surveys are reported in Table 13 for each species, along with the 2.5% and 97.5% quantiles of a bootstrap sample of size 300. Note that these estimates are based on all available habitat area and the catch rate of adult (>30cm) fish, *i.e.*, the biomass represents exploitable biomass.

Schnute and Haigh (2000) note the frequent agreement of biomass estimates obtained from the commercial fishery and those obtained from the research surveys. Their Fig. 6, reproduced here as Figure 22, compares the bootstrapped biomass distributions from commercial tows in the 2nd quarter with the Hecate Strait assemblage survey conducted in June. The observed biomass estimates for each of the four years 1995, 1996, 1998, and 2000 are shown as circles in each boxplot. Note that the commercial estimates shown in Table 13 differ because they represent the mean of the quarterly estimates rather than the 2nd quarter estimate alone.

Biomass surveys are also designed to sample as much of the potential habitat as possible in the region of interest, including areas of both high and low abundance of the target species. Conversely, the commercial data generally reflect areas where the target species occurs, or is thought to occur, in commercial densities. Thus, low or zero catch rates over marginal habitat may be underrepresented in the commercial catch data leading to positive bias in a swept area expansion estimator. One tactic to counter the bias is to restrict the area of extrapolation as in both Walters and Bonfil (1999) and Schnute and Haigh (2000). However, the result may be "minimum" estimates in the parlance of Walters and Bonfil (1999) or the relatively low estimates (Table 13) obtained by Schnute and Haigh (2000). Indeed, Schnute and Haigh (2000, their Fig.3c) report that biomass estimates derived from commercial data using the total available bathymetry (A) were factors of 14.51 and 11.63 greater than those derived from ground trawled (A^*) for rock and English soles, respectively. Similarly, biomass estimates produced from the Hecate Strait assemblage survey data were factors of 14.92 (rock sole) and 12.2 (English sole)

greater for estimates based on total bottom area compared to estimates based on trawled bottom area (Schnute and Haigh 2000, their Fig. 5). Other limitations to the approach are discussed by Schnute and Haigh (2000).

10 Yield Recommendations

Rock sole and English sole catches have declined over the last three years even though fishing effort has remained relatively stable for rock sole and has actually increased for English sole. We recognise that the crab closure is, in part, responsible for the decline in rock sole landings but the quota for both species has not been fully subscribed the last three years.

Recruitment for both species declined between 1995 and 1997 and remained low in 1998 and 1999. Without replacement the adult biomass of these stocks has been fished down and has continued to decline after 1997 due to low recruitment. Furthermore the trend in biomass for all of the swept area estimates is in agreement with the trend in biomass from the catch-age analysis. Previous analyses for both species suggest that production is impaired at low stock sizes (Fargo 1994, Fargo and Wilderbuer 2000). Further declines in biomass could lead to recruitment failures. In view of this we use conservative target fishing mortality reference points to estimate yields that will prevent further declines in the biomass of these two species.

10.1 Rock sole yield

We are most concerned about the low recruitment for the rock sole stock over the last two years. Without adequate recruitment, a fishing rate greater than M will drive a stock to extinction or to an extremely low level where recovery is doubtful. In the late 1980s spawning stock biomass per recruit analysis (Gabriel et al. 1989) allowed scientists to incorporate a stock-recruit relationship directly into yield per recruit type calculations and examine the effect of variable fishing mortality on stock production. Spawning stock biomass per recruit SSB/R analysis provided a biological reference point for stock assessment work (Sissenwine, M.P. and J.G. Sheperd 1987, Patterson 1992). In the case of rock sole the equilibrium reference points calculated in this analysis provide the framework for our advice concerning appropriate levels of yield and fishing mortality. Clark (1991) applied this type of analysis to Pacific halibut and suggested that the ratio where stock biomass was ~40% of the pristine biomass was most appropriate for sustainable management of that species. The fishing rate associated with that biomass was designated as $F_{40\%}$ equivalent to $F_{0.4}$ in our analysis (see below).

The value for C^* for rock sole was 772 t with h^* at 0.16, biomass B^* at 4857 t and with an initial biomass of 10,000 t. The spawner to recruit ratio S/R declined to 50% and 40% of the initial S/R at $h_{0.5} = 0.15$ and $h_{0.4} = 0.19$, respectively (Table 9, Figure 7). The instantaneous rates of fishing mortality $F_{0.5}$ and $F_{0.4}$ that correspond to $h_{0.5}$ and $h_{0.4}$ are 0.17 and 0.21, respectively.

As a precautionary strategy we used $h_{0.5}$ and $h_{0.4}$, the annual fishing mortality reference points, to estimate a yield range for the stock. Using the 1999 total biomass estimate of 3710 t

the yield estimate for $h_{0.5}$ (0.15), is 557 t. The yield estimate for $h_{0.4}$ (0.19), is 705 t. The yields associated with $F_{0.1}$ (0.22), F=M (0.20) and F=0.75M (0.15) were 733 t, 673 t and 517 t, respectively. Given the decline in recruitment in recent years we feel that remedial measures for this stock are necessary.

The cooling of ocean surface waters along the B.C. coast since 1998 should produce favourable temperature conditions for rock sole eggs and larvae (Forrester and Thomson 1969, Fargo and McKinnell 1989). The research survey CPUE for juvenile rock sole increased in 2000. However, it will take several years for these year-classes to recruit to the fishery and conservation measures should be taken now to ensure the spawning biomass is not depleted in the interim. In the mean time, the research survey will be used to monitor the condition of this stock. Another detailed assessment should be conducted for rock sole in 2001.

10.2 English sole yield

As in the case of rock sole we noted a significant decline in English sole biomass and recruitment. Of primary concern are the recruitments in 1998 and 1999 that are among the lowest on record. As in the case of rock sole we have used equilibrium calculations to provide biological reference points for this stock and use this framework for scientific advice concerning yield.

The value for C^* for English sole was 763t with h^* at 0.16, with biomass B^* at 4796 t and with an initial biomass of 10,000 t. The spawner to recruit ratio S/R declined to 50% and 40% of the initial S/R at $h_{0.5} = 0.14$ and $h_{0.4} = 0.18$. The instantaneous rates of fishing mortality that correspond to $h_{0.5}$ and $h_{0.4}$ are 0.15 and 0.20, respectively.

As a precautionary strategy we used the fishing mortality reference points $h_{0.5}$ and $h_{0.4}$ to estimate a yield range for this stock. Using the 1999 total biomass estimate, 2459 t the yield estimate for $h_{0.5}$, is 344 t. The yield estimate for $h_{0.4}$ was 443 t. The yields associated with $F_{0.1}$ (0.25), F=M (0.20) and F=0.75M (0.15) were 544 t, 446 t and 343 t, respectively. Given the decline in recruitment in recent years we feel that remedial measures are necessary. We recommend that another detailed assessment for English sole be conducted next year. In the mean time, the research survey will be used to monitor the condition of this stock.

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Literature Cited

Alderdice, D.F. and C.R. Forrester. 1969. Some effects of salinity and temperature on early development and survival of the English sole (*Parophrys vetulus*). J. Fish. Res. Bd. Can. 25: 495-521.

Anthony, V.C. 1982. The calculation of $F_{0.1}$; a plea for standardization. NAFO SCR Doc. 82/VI/64 Ser. No. N557: 15p.

Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations. U.K. Min. Agric. Fish., Fish. Invest. (Ser. 2) 19:553p.

Boehlert, G.W. and B.C. Mundy. 1987. Recruitment dynamics of metamorphosing English sole, *Parophrys vetulus* to Yaquina Bay, Oregon. Estuar. coast. Shelf Sci. 25: 261-268.

Chilton D.E. and R. J. Beamish. 1982. Age determination methods for fishes studies by the groundfish program at the Pacific Biological Station. Can. Spec. Pub. Fish. Aquat. Sci. 60: 102 p.

Clark, W.G. 1991. Groundfish exploitation rates based on life history parameters. Can. J. Fish. Aquat. Sci. 48: 734-750.

Demory, R.D. 1988. Status of the Pacific coast groundfish fishery through 1988 and recommended acceptable biological catches for 1989. Pacific Fishery Management Council. Metro Center, Suite 420. Portland, Oregon.

FAO 1995. Reference points for fisheries management. FAO Fisheries Technical Paper No. 347. Rome FAO. 83 p.

Fargo, J.1986. Hecate Strait fish-assemblage distribution surveys p. 4-10. *In:* A.V. Tyler [ed.] 1986. Hecate Strait Project: results of the first two years of multispecies fisheries research. Can. Tech. Rep. Fish. Aquat. Sci. 1470: 50 p.

Fargo, J.1989. Distribution of demersal fish assemblages. p. 9-26. In: A.V. Tyler [ed.]. 1989. Hecate Strait Project: results from fours of multispecies fisheries research. Can. Tech. Rep. Fish. Aquat. Sci. 1675: 60 p.

Fargo, J. 1994. Examining recruitment relationships for Hecate Strait English sole *(Pleuronectes vetulus)*. Neth. J. Sea Research 32(3/4):385-397.

Fargo, J. 1995. Flatfish. pp. 160-222. In Stocker, M. and J. Fargo [Ed.] Groundfish stock assessments for the west coast of Canada in 1994 and recommended yield options for 1995. Can. Tech. Rep. Fish. Aquat. Sci. 2069: 440 p.

Fargo, J. Flatfish. 1998. Flatfish Stock Assessments for the west coast of Canada for 1997 and recommended yield options for 1998. Canadian Stock Assessment Secretariat Research Document 97/36. 55p.

Fargo, J. Flatfish. 1999. Flatfish Stock Assessments for the west coast of Canada for 1999 and recommended yield options for 2000. Canadian Stock Assessment Secretariat Research Document 99/199. 30p.

Fargo, J., R.P. Foucher, S.C. Shields and D. Ross. 1984. English sole tagging in Hecate Strait, R/V G.B. REED, June 6-24, 1983. Can. Data Rep. Fish. Aquat. Sci. No. 427: iii + 49p.

Fargo, J., T. Hoyt and K. Robinson. 1982. Trawl survreys of juvenile flatfish in Hecate Strait, M/V Arctic Ocean, August 6-21, 1981. Can. Data Rep.Fish. Aquat. Sci. 324: 110p.

Fargo, J. and A.R. Kronlund. 1997. Flatfish stock assessments for the west coast of Canada for 1996 and recommended yield options for 1997. Can. Tech. Rep. Fish. Aquat. Sci. 2149: 124 p.

Fargo, J. and S. McKinnell 1989. Effects of temperature and stock size on year-class production for rock sole (*Lepidopsetta bilineata*) in northern Hecate Strait, British Columbia, p. 327-333. *In* R.J. and G.A. Mc Farlane [ed.] Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. Can. Spec. Publ. Fish. Aquat. Sci. 108.

Fargo, J. and T. Sexton. 1991. The ovarian histology of English sole (*Parophrys vetulus*). Can. Manuscr. Rep. Fish. Aquat. Sci. 2133: 19 p.

Fargo and Tyler. 1991. Sustainability of flatfish-dominated fish assemblages in Hecate Strait, British Columbia, Canada. Neth. J. of Sea Research 27 (3/4): 237-253.

Fargo, J. and A. V. Tyler. 1994. Oocyte maturation in Hecate Strait English sole (*Parophrys vetulus*). Fishery Bulletin 92:189-197.

Fargo, J. and S.J. Westrheim. 1987. Results, through 1985, of the rock sole (*Lepidopsetta bilineata*) tagging experiments in Hecate Strait (British Columbia) during April-May 1982 with regard to stock delineation. Can. MS. Rep. Fish. Aquat. Sci. 1912: 51p.

Fargo and Wilderbuer.(In press). Population dynamics of rock sole (*Lepidopsetta bilineata*) in the north Pacific. Neth. Journal Sea Research.

Forrester,C.R. 1969. Life history information on some groundfish species. Can. Tech. Rep. Fish. Aquat. Sci. 105: 17 p.

Forrester, C.R. and J. A. Thomson. 1969. Population studies on the rock sole (*Lepidopsetta bilineata*) of northern Hecate Strait British Columbia. Fish. Res. Board Can. 108: 104 p.

Foucher, R.P., A.V. Tyler, J. Fargo, and G.E. Gillespie. 1989. Reproductive biology of Pacific cod and English sole from the cruise of the F/V Blue Waters to Hecate Strait, January 30 to February 11, 1989. Can. MS. Rep. Fish. Aquat. Sci. 2026: 85 p.

Gabriel, W.L., M.P. Sissenwine and W.J. Overholtz. 1989. Analysis of spawning stock biomass per recruit: an example for Georges Bank haddock. North Am. J. Fish. Mgmt. 9: 383-391.

Hand, C.M., B.D. Robison, J. Fargo, G.D. Workman, and M. Stocker. 1994. R/V W.E. RICKER assemblage survey of Hecate Strait, May 17 - June 3, 1993. Can. Data. Rep. Fish. Aquat. Sci. 925: 197 p.

Hosmer, D.W. and D.W. Lemeshow. 1989.Applied Logistic Regression. Wiley-Interscience, New York, 219pp.

Ketchen, K.S. 1956. Factors influencing the survival of the lemon sole *(Parophrys vetulus)* in Hecate Strait, British Columbia. J. Fish. Res. Bd. Canada 13(5): pp. 647-694.

Ketchen, K.S. editor 1980. Assessment of groundfish stocks off the west coast of Canada (1979). Can. Data Rep. Fish. Aquat. Sci. No. 185: 213 p.

Ketchen, K.S. 1982. Stock delineation and growth of rock sole (Lepidopsetta bilineata) as indicated by tagging in British Columbia waters, 1944-66. Can. MS Rep. Fish. Aquat. Sci. 1683: 41p.

Kruse,G.H. and A.V. Tyler. 1983. Simulation of temperature and upwelling effects on the English sole (*Parophrys vetulus*) spawning season. Can. J. Fish. Aquat. Sci. 40: 230-237.

Kruse, G.H. and A.V. Tyler. 1989. Exploratory simulation of English sole recruitment mechanisms. Trans. Am. Fish. Soc. 118:101-118.

Leaman, J.E. and J.M. Hamer. 1985. User's guide to the groundfish catch statistics data system of the Fisheries Research Branch, Pacific Region, Can. Tech. Rep. Fish. Aquat. Sci. 1395: 31p.

Methot, R.D. 1990. Synthesis model: an adaptable framework for analysis of diverse stock assessment data. Int. Pac. Fish. Comm. Bull. 50: 259-277.

Orr and Matarese. 2000. Revision of the genus *Lepidopsetta* Gill, 1862. (Teleostei: Pleuronectidae) based on larval and adult morphology, with a description of a new species from the North Pacific Ocean and Bering Sea. Fish. Bull. 98:539-582.

Patterson, K. 1992. Fisheries for small pelagic species: an empirical approach to management targets. Reviews in Fish Biology and Fisheries, 2: 321-338.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters and mean environmental temperature in 175 fish stocks.J. Cons. CIEM 39(2): 175-192.

Perry, R.I., M. Stocker and J. Fargo. 1994. Environmental effects on the distributions of groundfish in Hecate Strait, British Columbia. Can. J. Fish. Aquat. Sci. 51: 1401-1409.

Quinn, T.J. 11. 1985. Catch-per-unit-effort: a statistical model for Pacific halibut *(Hippoglossus stenolepis)*. Can. J. Fish. Aquat. Sci. 42: 1423-1429.

Richards, L.J. and J. T. Schnute. 1986. An experimental and statistical approach to the question: Is CPUE an index of abundance? Can. J. Fish. Aquat. Sci. 43: 1214-1227.

Richards, L.J. and J.T. Schnute. 1992. Statistical models for estimating CPUE from catch and effort data. Can. J. Fish. Aquat. Sci. 49:7 pp. 1315-1327.

Rutherford, K.L. 1999. A brief history of GFCATCH (1954-1995), the groundfish catch and effort database at the Pacific Biological Station. Can. Tech. Rep. Fish. Aquat. Sci. 2299: 66p.

Schnute, J.T. and R. Haigh. 2000. Estimating stock biomass from tow-by-tow data for Pacific groundfish. Can. Stock Assess. Sec. Res. Doc. 2000/155.

Schnute, J.T., Olsen, N and R. Haigh. 1999. Slope rockfish assessment for the west coast of Canada in 1999. Can. Stock. Assess. Sec. Res. Doc. 99/184.

Schnute, J.T. and L.J. Richards. 1995. The influence of error on population estimates from catch-age models. Can. J. Fish. Aquat. Sci. 52:2063-2077.

Schnute, J.T. and L.J. Richards. 1998. Analytical models for fishery reference points. Can. J. Fish. Aquat. Sci. 55: 515-528.

Sissenwine, M.P. and J.G. Shepherd. 1987. An alternative perspective on recruitment overfishing and the biological reference points. Can. J. Fish. Aquat. Sci. 44: 913-18.

Shvetsov, F.G. 1979. Reproduction of the flounder Lepidopsetta bilineata off the Okhotsk Sea Coast near Paramushiro and Shumshu Islands. J. Ichthyol. 19 (5) 61-68.

Stanley, R.D. and D. Davenport. 1982. A study of trawl mesh selectivity for English sole and rock sole in Hecate Strait, August 1-5, 1980. Can. MS Rep. Fish. Aquat. Sci. 1637: 48 p.

Stocker, M. 1980. In: Assessment of groundfish stocks off the west coast of Canada in 1979 and Recommended Total Allowable Catches for 1980. Can. Data Rep. Fish. Aquat. Sci. 208: 265 p.

Stocker, M., J. Fargo, W.R. Harling, and S.E. MacLellan. 1981. Juvenile Flatfish Survey of M/V/ NUCLEUS, August 11-25, 1980. Can. Data Rep. Fish. Aquat. Sci. 297: 150 p.

Turnock, J., M. Wilkins, M. Saelens and B. Lauth. 1994. Status of west coast English sole in 1994. Status of the Pacific coast groundfish fishery through 1994 and recommended acceptable biological catches for 1995. Pacific Management Council. Vol. 1: p. C1-C62.

Turnock, J., M. Wilkins, M. Saelens and B. Lauth. 1995. Status of west coast English sole in 1995. Pacific Fishery Management Council, Portland, Oregon.

Walters, C.J. and R. Bonfil. 1999. Multispecies spatial assessment models for the British Columbia groundfish trawl fishery. Can. J. Fish. Aquat. Sci. 56: 601-628.

Westrheim, S.J. 1977. Production and Stock Assessment of Principal Groundfish Stocks off British Columbia. Fisheries & Marine Service Industry Report No. 94: 77p.

Wilderbuer, T.K. and G.E. Walters. 1999. Rock sole. In: Plan Team for the Groundfish Fisheries of the Bering Sea and Aleutian Islands. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Region, chap 6. N. Pac. Fish. Manage. Council. P.O. Box 103136, Anchorage, AK 99510.

Wilson, S.J., J. Fargo, C.M. Hand, T.J. Johansson and A.V. Tyler. 1991. R/V W.E. RICKER assemblage survey of Hecate Strait, June 3-22, 1991. Can. Data Rep. Fish. Aquat. Sci. 866: 179p.

Workman, G.D., J. Fargo, K.L. Yamanaka and V. Haist. 1996. R/V W.E. RICKER Assemblage Survey of Hecate Strait, May 23-June 9, 1995. Can. Fish. Aquat. Sci. Data Rep. No. 974: 94p.

Appendix A Catch Age Model Description

The catch-age model used for this assessment is derived from those proposed by Schnute and Richards (1995), Richards et al. (1997), and Fargo and Richards (1998). All these formulations follow the state-space design principles described by Schnute (1994). The notation for a model tailored to rock sole and English sole is presented in Table A.1. The model is stated deterministically in Table A.2. Stochastic variation is introduced in Table A.3 where four sources of variability are contemplated. These components of variation are related to system dynamics (process error) in the recruitment function and survival, and to measurement error in the observation of the stock index and the proportions at age. Table A.4 contains the likelihood functions corresponding to the deterministic model in Table A.2, where the survival error has been set to zero. The sequential components of the model are described below. Tables A.5 and A.6 list the likelihood function and maximum likelihood equations used for assessments prior to this document (e.g. Fargo 1999) for the sake of completeness.

Selectivity

Fishery selectivity $\{\beta_a\}_{a=1}^{A}$ was allowed by vary with age class as defined by equation (D.2). Selectivity for rock sole and English sole was modeled as a two-parameter function (D.2, where $(1 \le t' < t)$) in previous assessments (Fargo 1998). Selectivity increases from β_1 to 1 as a ranges from age class 1 to accumulator age class A. Age class 1 is defined as the youngest age included in the input data. The accumulator age class A includes all fish equal to, or older than, the designated maximum age in the model. Selectivity is linear when the "slope" parameter $\alpha = 1$ and is convex downwards when $\alpha > 1$ with slope 0 at age a=A.

A management regulation imposed in 1995 required that the trawl fleet adopt a 6 inch codend mesh size in place of the formerly used 4.5 inch codend mesh size. Consequently, two modifications to the selectivity function were examined in this assessment. The first modification to selectivity involved fitting curves (D.2) corresponding to the periods before and after inception of the mesh regulation in year $t' = 1995$. The post-regulation period was parameterized so that the value of the selectivity of the first age class, β_1, could vary by an offset Δ, but shared a common slope parameter α with the pre-regulation period. Thus, the case $\Delta = 0$ results in a test of the hypothesis of no significance difference in the selectivity of the first age class before and after the mesh regulation.

State Moments

The exploitable population P_t, exploitable population biomass B_t, and exploitable age proportions u_{at}, depend on the selectivity vector through equations (D.3-D.5). The catch biomass D_t is assumed to be known without error and is converted to catch numbers C_t by equation (D.6) using the mean weights w_{at}. Spawning biomass B_t is computed using maturity at age m_a by equation (D.7).

Recruitment

Recruitment equations in Table A.3 are derived from a lognormal autoregressive recruitment process

(1) $\log R_t = \log R + \gamma(\log R_{t-1} - \log R) + \sigma_1 \delta_t$

with parameters (R, γ, σ_1) and where the δ_t are independent standard normal variates (Schnute and Richards 1995). This function (1) has the property that if $\gamma = 0$ then log R is normal with mean log R and variance σ_1^2. As the autocorrelation parameter $\gamma \to 1$ the process approaches a random walk with finite moments

(2) $E[\log R_t \mid R_{t-1}] = (1-\gamma)\log R + \gamma \log R_{t-1}$,

(3) $Var[\log R_t \mid R_{t-1}] = \sigma_1^2$,

but infinite unconditional variance

(4) $Var[\log R_t] = \sigma_1^2 / (1-\gamma^2)$.

Predicted Observations

Observed data are related to the underlying biological system by equations (D.14-D.16), where an estimated observation is denoted by a bar over the quantity. Observed data are derived from research surveys and commercial fishery data, and from proportions at age determined from port samples of the commercial catch.

Stock Abundance Indices

Recent assessments of flatfishes have relied on a single catch per unit effort index derived from the Hecate Strait assemblage survey data (Fargo 1999). Two stock indices are possible in this model to allow data from both the Hecate Strait assemblage survey and from the commercial fishery to be incorporated. Data from the Hecate Strait survey (1984, 1987, 1989, 1991, 1993, 1995, 1996, 1998) was used to develop an adult catch rate index (see section 7.4). A commercial index, median catch per unit effort, was derived from commercial fishery data for the years 1944 to 1994 inclusive. Commercial data from 1996 onwards was not used because the inception of on-board observer coverage in 1996 and the individual quota system in 1997. Expected changes in fleet behavior as a result of these management measures (e.g. "avoidance" fishing, achieving individual flatfish quotas through bycatch) suggest that recent catch rate data may not be comparable to the historical series.

Stock abundance indices are incorporated through equations (D14) and (D.15). The survey and commercial abundance indices (I_{1t}, I_{2t}) are assumed to be proportional to the

exploitable biomass after known fractions (f_{1t}, f_{2t}) of the catch are removed. For example, the survey fraction f_{1t} represents that portion of the annual catch taken at the time the survey was conducted. For this analysis, $f_{1t} = 0.5,\ t \in \mathbf{T}_1$ and $f_{2t} = 0.5,\ t \in \mathbf{T}_2$. The model can be rendered for a single tuning index simply by removing the first product in equation (L.10).

Proportions at age

The proportions p_{at} are estimated using the exploitable proportions u_{at} calculated in equation (D.16). For rock and English soles, the age-class a=1 corresponds to fish that recruit at age 4, while the accumulator age class A=9 consists of all fish age 12 and older.

A multivariate logistic error structure (S.10, L.8) was adopted for the proportions at age for two reasons. First, the observed proportions at age may be suspected to have higher variances than expected if the data were drawn from a multinomial distribution. Second, the logistic distribution provides a simple transformation that ensures the model proportions sum to one but allows model parameters to be unconstrained (Schnute and Richards 1995, Quinn and Deriso 1999, p. 332).

Sequential Algorithm

The model described in Table A.2 includes a population state vector $\{N_{at}\}_{a=1}^{A}$ for each year t with system dynamics for these states defined by equations (D.9)-(D.13). These dynamics are a consequence of the parameter vector $\ddot{\mathbf{O}}$ and the control data defined by catch biomass (D_t), mean fish weight at age a and time t (w_{at}), maturity at age a (m_a) and the observed proportions at age a and time t (p_{at}). The parameter vector $\ddot{\mathbf{O}}$ includes the recruitments $\{R_t\}_{t=2-A}^{T}$ that determine the initial states N_{a1} at time t=1 using equations (D.9) and (D.10) and the initial moments from equations (D.3) to (D.8). At time t=2, the states N_{a2} are determined using the dynamic equations (D.11)-(D.13) and the previously computed values (N_{a1}, C_1, u_{a1}). Iterative application of this procedure yields values N_{at} for all values of time $t = 2,\ldots,T$. Estimated observations are produced by application of equations (D.14)-(D.16) to the values of the states and moments determined at each iteration.

Unit Analysis

The recruitment vector $\{R_t\}_{t=A-2}^{T}$ determine the units of the numbers of fish N_{at} by equation (D.9-D.13). The catch in numbers C_t is in units of millions of fish since the observed catch biomass D_t, (thousands of tonnes) is divided by the mean weight per fish w_{at} (kilograms). Hence, the recruitment units are millions of fish. Exploitable biomass B_t is in units of millions of kilograms, or thousands of tonnes, by equation (D.4). Spawning biomass is also in millions of kilograms (thousands of tonnes) by equation (D.7).

Sources of error

The sources of error are (1) autoregressive lognormal process error among the recruitments R_t with recruitment standard deviation σ_1 (2) lognormal measurement error in the stock indices (I_{1t}, I_{2t}) with index standard deviation τ_1, and (3) multivariate logistic measurement error in the observed age proportions p_{at} with standard deviation τ_2. We have assumed that the standard deviation τ_1 applies to both stock indices. This is reasonable since the index residuals defined by equations (L.6, L.7) are formed from the log of ratios and are therefore dimensionless. Also, error in the survival process represented by equations (S.5, S.7) of Table A.3 has been ignored by setting $\sigma_2 = 0$.

In order to avoid singularities in the maximum likelihood function (L.11) (Schnute 1994, Schnute and Richards 1995), we reduce the number of parameters by assuming a known variance ratio between recruitment process error and stock index measurement error. Equation (L.2) defines the total variance κ^2 resulting from the two error components and ρ is the proportion of this variance attributable to the recruitment process error. The definition (L.2) re-parameterizes the recruitment and index errors from (σ_1, τ_1) to (κ^2, ρ), while equation (L.3) reverses the transformation. Note that a given choice of ρ implies the variance ratio

$$(5) \qquad \frac{\sigma_1^2}{\tau_1^2} = \frac{\rho}{1-\rho} \ .$$

Thus, as $\rho \to 0$, recruitment becomes more deterministic $(\sigma_1 \to 0)$. Similarly, measurement error assigned to the stock indices diminishes as $\rho \to 1$ and therefore $\tau_1 \to 0$.

Likelihood Function

Table A.4 defines the likelihood function $L(\grave{\mathbf{E}})$ for the stochastic model, where the parameter vector $\grave{\mathbf{E}}$ includes the vector $\ddot{\mathbf{O}}$ in equation (D.1) plus the parameters $(R, \gamma, \sigma_1, \tau_1, \tau_2)$. Computation of the likelihood function begins with the values of $\bar{p}_{at}$ and $\bar{I}_{it}$ from Table A.2 and proceeds through equations (L.4)-(L.12).

Technical Issues

Technical details related to model implementation are omitted from the model description in Tables A.2 through A.5 to simplify notation. Implementation details include the following items.

1. The state-space formulation accommodates missing information. The absence of Hecate Strait survey data prior to 1984, and the absence of survey index data in 1985, 1986,

1988, 1990, 1992, 1994, 1997 and 1999 (Table A.) require that terms be dropped from the product (L.10).

2. In order to reduce the influence of age class proportions based on only a few fish, the definition of an age class was altered to require that $p_{at} \geq 0.02$ for all a and t in the manner of Richards et al. (1997). This requirement was implemented in computer code by grouping consecutive ages into a single age class whenever necessary. When a proportion was less than or equal to 0.02 for a given age class a, the observed numbers at age a were added to the observed numbers at age classes a+1, a+2, ... until the proportion exceeded 0.02.

3. Removing the effects of the stock indices can be achieved by fixing any two of $(\rho, \kappa^2, \sigma_1^2)$ appropriately. In particular, fix ρ at some small value (e.g. 0.0001) and fix σ_1^2 at some sensible value by setting $\kappa^2 = \sigma_1^2 / \rho$ as implied by equation (L.3). As a consequence, κ^2 will be large, and hence τ_1^2 will be large. This effectively reduces the weight of $L_2(\grave{\mathbf{E}})$ of equation (L.10) in the overall likelihood $L(\grave{\mathbf{E}})$ defined in equation (L.12).

Table A.1. Notation for the flatfish catch-age model.

Symbol	Description
	Indices and index ranges
a	Age class, where 1<= a <=A and a =1 corresponds to first age class
t	Year, where 1<= t <=T and t =1 corresponds to the first year
A	Accumulator age class
T	Final year
$\mathbf{T}_1, \mathbf{T}_2$	Sets of years for stock index 1 and stock index 2
	Data
D_t	Observed catch biomass in year t
f_{1t}, f_{2t}	Fraction of catch taken prior to measurement of stock indices
I_{1t}, I_{2t}	Observed stock indices in year t
m_a	Proportion of age class a fish that are mature
p_{at}	Observed proportion of age class a fish in the catch for year t
w_{at}	Mean weight of age class a fish in year t
	Parameters
$\dot{\mathbf{E}}, \ddot{\mathbf{O}}$	Vectors of model parameters
α	Selectivity slope parameter
β_1	Selectivity of age class a=1, for years $(1 \le t < t')$
Δ	Difference in selectivity of age class a=1, for years $(t' \le t \le T)$
β_a	Selectivity for age class a
M	Instantaneous rate of natural mortality
q_1, q_2	Scaling factor (catchability) for stock indices
R, γ	Autoregressive recruitment parameters
σ_1	Standard deviation of recruitment process error
τ_1	Standard deviation of stock index measurement error
τ_2	Standard deviation of age proportion measurement error
κ^2	Total recruitment process error and stock index measurement error
ρ	Variance ratio σ_1/κ^2
	States and state moments
B_t	Exploitable biomass at the start of year t
C_t	Number of fish caught in year t
F_t	Instantaneous fishing mortality rate in year t
N_{at}	Number of age class a fish at the start of year t
P_t	Exploitable numbers at the start of year t
R_t	Age class a=1 recruitment in year t
S_t	Spawning biomass at the start of year t
u_{at}	Exploitable proportion of age class a fish in year t catch

Table A.2. Deterministic catch-age model listing recursive calculations that define all states and observations given the parameter vector $\ddot{\mathbf{O}}$.

Parameters

(D.1) $\ddot{\mathbf{O}} = \left(\alpha, \beta_1, \Delta, M, q_1, q_2, \{R_t\}_{t=2-A}^{T}\right)$

Selectivity

(D.2) $$\beta_{at} = \begin{cases} 1-(1-\beta_1)\left(\dfrac{A-a}{A-1}\right)^{\alpha}; & (1 \le t < t') \\ 1-(1-\beta_1+\Delta)\left(\dfrac{A-a}{A-1}\right)^{\alpha}; & (t' \le t \le T) \end{cases}$$

State Moments

(D.3) $P_t = \sum_{a=1}^{A} \beta_{at} N_{at}$

(D.4) $B_t = \sum_{a=1}^{A} \beta_{at} w_{at} N_{at}$

(D.5) $u_{at} = \beta_{at} N_{at} / P_t; \quad (1 \le a \le A)$

(D.6) $C_t = D_t \Big/ \sum_{a=1}^{A} u_{at} w_{at}$

(D.7) $S_t = \sum_{a=1}^{A} m_a w_{at} N_{at}$

(D.8) $F_t = \log\left(\dfrac{P_t}{P_t - C_t}\right)$

Initial States $(t=1)$

(D.9) $N_{a1} = R_{2-a} e^{-M(a-1)}; \quad (1 \le a < A)$

(D.10) $N_{A1} = R_{2-A}\left(\dfrac{e^{-M(A-1)}}{1-e^{-M}}\right)$

State Dynamics $(2 \le t \le T)$

(D.11) $N_{1t} = R_t$

(D.12) $N_{at} = e^{-M}\left[N_{a-1,t-1} - u_{a-1,t-1} C_{t-1}\right]; \quad (2 \le a < A)$

(D.13) $N_{At} = e^{-M}\left[N_{A-1,t-1} + N_{A,t-1} - \left(u_{A-1,t-1} + u_{A,t-1}\right) C_{t-1}\right]$

Predicted Observations $(1 \le t \le T)$

(D.14) $\bar{I}_{1t} = q_1 (B_t - f_{1t} D_t); \quad (t \in \mathbf{T}_1)$

(D.15) $\bar{I}_{2t} = q_2 (B_t - f_{2t} D_t); \quad (t \in \mathbf{T}_2)$

(D.16) $\bar{p}_{at} = u_{at}; \quad (1 \le a \le A)$

Table A.3. Stochastic catch-age simulation model. Predicted values from Table A.1 are indicated using a bar over the quantity. The standard normal variates $(\omega_t, \delta_{at}, \upsilon_{it}, \varepsilon_{at})$ are mutually independent.

Parameters

(S.1) $\grave{\mathbf{E}}_S = (\alpha, \beta, \Delta, M,\ q,\ q_2,\ R, \gamma, \sigma, \sigma_2, \tau_1, \tau_2)$

Recruitment $(2-A \le t \le T)$

(S.2) $R_{2-A} = Re^{\left(\sigma_1/\sqrt{1-\gamma^2}\right)\omega_{2-A}}$

(S.3) $R_t = R^{1-\gamma} R_{t-1}^{\gamma} e^{\sigma_1 \omega_t}, \quad 2-A < t \le T$

Initial States $(t=1)$

(S.4) $N_{11} = R_1$

(S.5) $N_{a1} = \bar{N}_{a1} \prod_{b=2}^{a} \frac{e^{\sigma_2 \delta_{b\ b-a+1}}}{1-e^{-M}+e^{-M} e^{\sigma_2 \delta_{b\ b-a+1}}}, \quad 2 \le a \le A$

State dynamics $(t \ge 2)$

(S.6) $N_{1t} = R_t$

(S.7) $N_{at} = \bar{N}_{at} \frac{e^{\sigma_2 \delta_{at}}}{1-e^{-M}+e^{-M} e^{\sigma_2 \delta_{at}}}, \quad 2 \le a \le A$

Observations $(1 \le t \le T)$

(S.8) $I_{1t} = \bar{I}_{1t} e^{\tau_1 \upsilon_{1t}}$

(S.9) $I_{2t} = \bar{I}_{2t} e^{\tau_1 \upsilon_{2t}}$

(S.10) $x_{at} = \log(\bar{p}_{at}) + \tau_2 \varepsilon_{at} - \frac{1}{A} \sum_{a=1}^{A} \left[\log(\bar{p}_{at}) + \tau_2 \varepsilon_{at} \right]; \quad (1 \le a \le A)$

(S.11) $p_{at} = \frac{e^{x_{at}}}{\sum_{a=1}^{A} e^{x_{at}}}; \quad (1 \le a \le A)$

Table A.4. Likelihood function for the model in Table A.2 where sequential calculations begin with the parameter vector $\dot{\mathbf{E}}$ and proceed to define $L(\dot{\mathbf{E}})$.

Parameters

(L.1) $\dot{\mathbf{E}} = (\ddot{\mathbf{O}}, R, \gamma, \sigma_1, \tau_1, \tau_2)$

(L.2) $\kappa^2 = \sigma_1^2 + \tau_1^2, \quad \rho = \dfrac{\sigma_1^2}{\sigma_1^2 + \tau_1^2}$

(L.3) $\sigma_1^2 = \rho\kappa^2, \quad \tau_1^2 = (1-\rho)\kappa^2$

Residuals

(L.4) $\xi_{2-A} = \log R_{2-A} - \log R$

(L.5) $\xi_t = \log R_t - (1-\gamma)\log R - \gamma \log R_{t-1}; \quad (2-A < t \le T)$

(L.6) $\zeta_{1t} = \log I_{1t} - \log \bar{I}_{1t}; \quad (t \in \mathbf{T}_1)$

(L.7) $\zeta_{2t} = \log I_{2t} - \log \bar{I}_{2t}; \quad (t \in \mathbf{T}_2)$

(L.8) $\eta_{at} = \log(p_{at}) - \log(\bar{p}_{at}) - \dfrac{1}{A}\sum_{a=1}^{A}\left[\log(p_{at}) - \log(\bar{p}_{at})\right]$

Likelihoods

(L.9) $L_1(\dot{\mathbf{E}}) = \sqrt{1-\gamma^2}\left(\sqrt{2\pi}\sigma_1\right)^{2-A-T} \exp\left[-\dfrac{1}{2\sigma_1^2}\left((1-\gamma^2)\xi_{2-A}^2 + \sum_{t=3-A}^{T}\xi_t^2\right)\right]$

(L.10) $L_2(\dot{\mathbf{E}}) = \prod_{i=1}^{2}\prod_{t\in\mathbf{T}_i}\left[\dfrac{1}{\sqrt{2\pi}\tau_1}\exp\left(-\dfrac{1}{2\tau_1^2}\zeta_{it}^2\right)\right]$

(L.11) $L_3(\dot{\mathbf{E}}) = \prod_{t=1}^{T}\left[\dfrac{A^{V2}}{\left(\sqrt{2\pi}\tau_2\right)^{A-1}}\exp\left(-\dfrac{1}{2\tau_2^2}\sum_{a=1}^{A}\eta_{at}^2\right)\right]$

(L.12) $L(\dot{\mathbf{E}}) = \prod_{i=1}^{3} L_i(\dot{\mathbf{E}})$

Table A.5. Likelihood function for the historical catch-age model used in assessments prior to 2000. Sequential calculations begin with the parameter vector $\grave{\mathbf{E}}_{II}$ and proceed to define $L(\grave{\mathbf{E}}_{II})$.

Parameters

(H.1) $$\grave{\mathbf{E}}_{II} = \left(\alpha, \beta, M, q, R, \gamma, \{R_t\}_{t=2-A}^{T}, \sigma_1, \tau_1, \tau_2\right)$$

(H.2) $$\kappa^2 = \sigma_1^2 + \tau_1^2, \quad \rho = \frac{\sigma_1^2}{\sigma_1^2 + \tau_1^2}$$

(H.3) $$\sigma_1^2 = \rho\kappa^2, \quad \tau_1^2 = (1-\rho)\kappa^2$$

Residuals

(H.4) $$\xi_{2-A} = \log R_{2-A} - \log R$$

(H.5) $$\xi_t = \log R_t - (1-\gamma)\log R - \gamma \log R_{t-1}; \quad (2-A < t \le T)$$

(H.6) $$\zeta_t = \log I_t - \log \bar{I}_t; \quad (t \in \mathbf{T})$$

(H.7) $$\eta_{at} = \log(p_{at}) - \log(\bar{p}_{at}) - \frac{1}{A}\sum_{a=1}^{A}\left[\log(p_{at}) - \log(\bar{p}_{at})\right]$$

Likelihoods

(H.8) $$L_1(\grave{\mathbf{E}}_{II}) = \sqrt{1-\gamma^2}\left(\sqrt{2\pi}\sigma_1\right)^{2-A-T} \exp\left[-\frac{1}{2\sigma_1^2}\left((1-\gamma^2)\xi_{2-A}^2 + \sum_{t=3-A}^{T}\xi_t^2\right)\right]$$

(H.9) $$L_2(\grave{\mathbf{E}}_{II}) = \left(\sqrt{2\pi}\tau_1\right)^{-T} \exp\left[-\frac{1}{2\tau_1^2}\sum_{t=1}^{T}\zeta_t^2\right]$$

(H.10) $$L_3(\grave{\mathbf{E}}_{II}) = \left(\sqrt{2\pi}\tau_2\right)^{-T(A-1)} A^{T/2} \exp\left[-\frac{1}{2\tau_2^2}\sum_{a=1}^{A}\sum_{t=1}^{T}\eta_{at}^2\right]$$

(H.11) $$L(\grave{\mathbf{E}}_{II}) = \prod_{i=1}^{3} L_i(\grave{\mathbf{E}}_{II})$$

Table A.6. Maximum likelihood estimates for the historical catch-age model defined in Table A.5. Results for the special case of $\rho = 0$ are listed.

$$\rho = 0$$

(E.1) $\ddot{\mathbf{O}}_L = (\alpha, \beta, M, q, R)$

(E.2) $\hat{\kappa}^2 = \hat{\tau}_1^2 = \frac{1}{T}\sum_{t=1}^{T} \zeta_t^2$

(E.3) $\hat{\tau}_2^2 = \frac{1}{(A-1)T}\sum_{a=1}^{A}\sum_{t=1}^{T} \eta_{at}^2$

(E.4) $\ell = T \log \hat{\kappa}^2 + (A-1)T \log \hat{\tau}_2^2$

$$0 < \rho < 1$$

(E.5) $\ddot{\mathbf{O}}_L = \left(\alpha, \beta, M, q, R, \gamma, \{R_t\}_{t=2-A}^{T}\right)$

(E.6) $\hat{\kappa}^2 = \frac{1}{A+2T-2}\left[\frac{1}{\rho}\left((1-\gamma^2)\xi_{2-A}^2 + \sum_{t=3-A}^{T} \xi_t^2\right) + \frac{1}{1-\rho}\sum_{t=1}^{T} \zeta_t^2\right]$

(E.7) $\hat{\tau}_2^2 = \frac{1}{(A-1)T}\sum_{a=1}^{A}\sum_{t=1}^{T} \eta_{at}^2$

(E.8) $\ell = (A+T-2)\log\rho + T\log(1-\rho) - \log(1-\gamma^2)$
$+ (A+2T-2)\log\hat{\kappa}^2 + (A-1)T\log\hat{\tau}_2^2$

Appendix B Equilibrium reference point calculations

We used the reference point calculations described by Schnute et al. (1999), which are adapted from work by Schnute and Richards (1998). These reference point calculations follow from equilibrium conditions for the state-space catch-age model used in the assessment, although we do not present proofs here. There are eight state variables for each year $t = 1,\ldots,T$ listed in the following table

Quantity	Description	Units
R_t	Recruitment at the start of year t	Numbers of fish
P_t	Population at the start of year t	Numbers of fish
B_t	Biomass at the start of year t	Weight
W_t	Mean weight of all fish in year t	Weight
A_t	Mean age of all fish in year t	Years
h_t	Harvest rate in year t	Dimensionless
C_t	Catch biomass in year t	Weight
S_t	Spawning biomass at the end of year t	Weight

Fish are assumed to recruit at age r, when the fish have weight w_r. Growth parameters determined using the von Bertalanffy model

(1) $$w_a = w_\infty\left[1-e^{-K(a-a_0)}\right],$$

are converted to Brody relationship parameters using the transition equations

(2) $$w_r = w_\infty\left[1-e^{-K(a-a_0)}\right],\quad \lambda=\left(1-e^{-K}\right)w_\infty,\quad \kappa=e^{-K}.$$

Recruitment follows a general function that includes Beverton-Holt $(\gamma=-1)$ and Ricker $(\gamma=0)$ relationships as special cases

(3) $$R_t = \alpha S_{t-1}\left(1-\beta\gamma S_{t-r}\right)^{1/\gamma}.$$

In year t, new recruits and survivors from year t-1 are reduced by fractions $1-\delta$ and $1-h_t$ that correspond to natural mortality and fishing mortality, respectively. Schnute et al. (1999) gave a set of recursive dynamic equations that yield equilibrium values if h_t is held constant for many iterations. These equilibrium values are given by the following sequential equations

(4) $$\sigma(h)=(1-\delta)(1-h)$$

(5) $$A(h) = r + \frac{\sigma}{1-\sigma}$$

(6) $$W(h) = \frac{(1-\sigma)\, w_r + \sigma\lambda}{1-\kappa\sigma}$$

(7) $$\rho(h) = \frac{1-\sigma}{(1-h)W}$$

(8) $$R(h) = \frac{\rho}{\beta\gamma}\left[1-\left(\frac{\rho}{\alpha}\right)^{\gamma}\right]$$

(9) $$P(h) = \frac{R}{1-\sigma}$$

(10) $$B(h) = WP$$

(11) $$C(h) = hB$$

(12) $$S(h) = B - C \ .$$

Given the recruitment age r, and a fixed harvest rate h, the calculations (A.4 to A.12) depend on seven parameters

(13) $$\theta = (\alpha, \beta, \gamma, \delta, w_r, \lambda, \kappa) \ .$$

Biologically, $\sigma(h)$ represents survival from fishing and natural mortality, and $\rho(h)$ denotes the recruit to spawner ratio $R(h)/S(h)$.

Suppose the subscript 0 indicates the unfished equilibrium value. The unfished recruit to spawner ratio $\rho_0 = R_0/S_0$ defines the recruitment productivity for the stock. Let the increase in productivity from an unfished stock S_0 to a small stock S be represented by the "steepness" $\phi = \alpha/\rho_0$, where $\alpha > \rho_0$ so that $\phi > 1$. Then, without proof, the following two results can be obtained

(14) $$\alpha = \frac{\phi\delta(1-\kappa+\kappa\delta)}{\delta w_r + (1-\delta)\lambda}$$

(15) $$\beta = \frac{1}{\gamma B_0}\left(1-\phi^{-\gamma}\right) .$$

Thus, the recruitment parameters (α,β,γ) can be replaced by (ϕ, B_0, γ) to yield a new parameter vector

(16) $$\theta' = (\phi, B_0, \gamma, \delta, w_r, \lambda, \kappa) ,$$

where the choice of B_0 sets the scale of the analysis. Common reference points can be computed from plots of the state variables against the harvest rate. Following the notation of Schnute et al. (1999), we use the following conventions

values associated with maximum sustained yield are denoted by a superscript asterisk, e.g. (C^*, h^*, B^*);

values corresponding to stock extinction are denoted by a superscript pound sign, e.g. $(C^\#, h^\#)$;

a percentage subscript denotes the percentage reduction of the ratio S/R from the unfished value S_0/R_0, e.g. $(C_{50\%}, h_{50\%})$;

a subscript (no percentage sign) denotes the values corresponding to an F target reference point, e.g. the fishing mortality $F_{0.1}$ corresponds to a fishing mortality of $h_{0.1}$, with associated yield per recruit at $(h_{0.1}, C_{0.1}/R_{0.1})$.

Table 1. Number of observations of biological measurements for rock sole from commercial and research survey data.

Year	Length	Sex	Age	Maturity
1945	758	758	758	0
1946	3604	3604	3604	0
1947	3553	3553	3553	0
1948	3860	3860	3860	0
1949	2749	2749	2749	0
1950	2646	2646	2646	0
1951	2425	2425	2425	0
1952	5579	5579	5579	0
1953	3323	3323	3323	0
1954	3166	3166	3166	0
1955	1561	1561	1561	0
1956	8005	8005	1048	0
1957	13607	13607	827	0
1958	14322	14322	1279	0
1959	6994	6994	858	0
1960	9845	9743	1165	0
1961	7635	7635	443	0
1962	12371	12371	548	0
1963	8901	8901	692	0
1964	11106	11106	552	0
1965	7674	7674	502	0
1966	18322	18322	1413	0
1967	12111	12111	684	0
1968	12349	12349	1469	0
1969	8742	8742	1380	0
1970	3296	3296	517	0
1971	4163	4163	480	0
1972	1165	1165	324	0
1973	3759	3759	469	0
1974	1468	1468	170	0
1975	1148	1148	428	0
1976	3780	3780	452	0
1977	8397	8397	1124	0
1978	3456	3456	999	0
1979	1262	1262	935	0
1980	4622	4622	294	2686
1981	7437	2586	300	413
1982	4088	2270	301	652
1983	1267	600	301	299
1984	630	630	293	300
1985	1016	1016	491	300
1986	2750	2749	441	2319
1987	1156	1155	478	1123
1988	1903	1903	701	1437
1989	1131	1133	282	757
1990	989	989	410	989
1991	1108	1108	99	1108
1992	962	962	270	962
1993	6059	477	337	365
1994	1167	1167	242	1147
1995	4412	1407	157	961
1996	12914	2232	353	1715
1997	570	401	322	401
1998	8155	1021	671	671
1999	7298	1021	311	917
2000	1402	104	-	-

Table 2. Number of observations of biological measurements for English sole from commercial and survey data.

Year	Length	Sex	Age	Maturity
1953	11310	11310	2146	0
1954	12224	12224	2238	0
1955	11151	11151	1123	0
1956	10527	10527	1060	0
1957	6829	6829	643	0
1958	11150	11150	1068	0
1959	8783	8783	1008	0
1960	8592	8592	1216	0
1961	11826	11826	1119	0
1962	7781	7781	722	0
1963	7732	7732	1093	0
1964	6318	6318	768	0
1965	6713	6713	875	0
1966	6540	6540	961	0
1967	4922	4922	876	0
1968	4548	4548	589	0
1969	5979	5979	1257	0
1970	5354	5354	972	0
1971	2853	2853	731	0
1972	1166	1166	646	0
1973	1922	1922	560	0
1974	813	813	298	0
1975	1645	1645	906	0
1976	1444	1444	627	0
1977	4046	4046	1360	0
1978	2353	2353	242	0
1979	4553	4553	900	0
1980	3258	3258	579	932
1981	600	600	300	200
1982	1742	1742	548	400
1983	1926	1388	259	332
1984	1508	1508	203	212
1985	2141	2141	400	0
1986	424	424	201	0
1987	541	465	100	465
1988	697	697	100	697
1989	134	134	50	50
1990	743	743	100	743
1991	501	501	50	501
1992	701	701	357	701
1993	705	705	393	617
1994	835	835	300	767
1995	1841	1841	389	909
1996	16489	1508	384	656
1997	831	687	471	588
1998	11292	900	294	607
1999	5017	569	163	473
2000				

Table 3. Rock sole landing statistics from the Hecate Strait trawl fishery, 1945 to 1999.

Year	Landings (t)[1]	Effort (hrs)[2]	CPUE (t/hr)[3]
1945	121	434	0.279
1946	410	2228	0.184
1947	1181	1946	0.607
1948	901	1753	0.514
1949	657	1352	0.486
1950	784	1452	0.540
1951	1024	944	1.085
1952	2292	2014	1.138
1953	779	1227	0.635
1954	926	840	0.938
1955	1560	1558	0.680
1956	1160	1484	0.644
1957	1151	2019	0.443
1958	1256	1331	0.650
1959	416	636	0.403
1960	1127	1100	0.680
1961	744	694	0.900
1962	829	849	0.735
1963	881	735	0.737
1964	743	835	0.531
1965	879	629	0.545
1966	2544	2491	0.598
1967	2162	2324	0.511
1968	2366	4209	0.386
1969	1461	4485	0.314
1970	1403	3660	0.326
1971	1503	3587	0.255
1972	515	650	0.337
1973	507	619	0.435
1974	622	603	0.475
1975	1204	1912	0.360
1976	1438	1830	0.402
1977	846	1896	0.285
1978	874	1662	0.336
1979	1313	1943	0.330
1980	977	2420	0.254
1981	584	806	0.287
1982	291	841	0.209
1983	247	499	0.286
1984	188	573	0.188
1985	112	276	0.242
1986	219	470	0.345
1987	536	577	0.389
1988	1402	2520	0.410
1989	1422	3757	0.288
1990	1519	3948	0.319
1991	2666	6552	0.295
1992	2226	5777	0.289
1993	2080	5851	0.301
1994	1384	4282	0.275
1995	1294	3538	0.322
1996	670	2336	0.207
1997	677	2667	0.191
1998	576	2395	0.182
1999	401	1709	0.169

[1] Canada-U.S. landings for PMFC Areas 5C and 5D

[2] Landings/CPUE

[3] Median CPUE for 25% qualified landings

Table 4. English sole landing statistics from the Hecate Strait trawl fishery, 1944 to 1999.

Year	Landings (t)	Effort (hrs)	CPUE (t/hr)
1944	152	215	0.707
1945	304	365	0.832
1946	470	809	0.581
1947	350	538	0.651
1948	937	2740	0.342
1949	795	1893	0.420
1950	2622	4910	0.534
1951	1024	2142	0.478
1952	1347	3293	0.409
1953	871	2084	0.418
1954	455	563	0.362
1955	875	744	0.401
1956	956	1344	0.349
1957	552	640	0.244
1958	693	617	0.337
1959	940	772	0.315
1960	1147	1058	0.333
1961	871	1615	0.298
1962	459	903	0.247
1963	408	568	0.207
1964	436	441	0.272
1965	414	326	0.317
1966	362	354	0.302
1967	534	535	0.411
1968	671	844	0.302
1969	819	1314	0.390
1970	1002	2042	0.312
1971	488	1585	0.192
1972	371	550	0.230
1973	667	514	0.411
1974	500	519	0.519
1975	938	1015	0.466
1976	1133	1627	0.275
1977	1179	2201	0.310
1978	559	944	0.246
1979	864	980	0.337
1980	995	1105	0.327
1981	1327	2149	0.249
1982	428	1062	0.219
1983	430	834	0.240
1984	658	1129	0.290
1985	585	1520	0.226
1986	335	469	0.365
1987	630	396	0.347
1988	688	540	0.493
1989	826	925	0.385
1990	992	1335	0.383
1991	913	940	0.308
1992	987	1602	0.307
1993	1421	2636	0.295
1994	1000	1860	0.343
1995	1190	2321	0.320
1996	455	570	0.310
1997	554	1286	0.227
1998	492	1725	0.261
1999	368	2178	0.116

[1] Canada-U.S. landings for PMFC Areas 5C and 5D
[2] Landings/CPUE
[3] Median CPUE for 25% qualified landings

Table 5. Management history for rock sole and English sole in the Hecate Strait trawl fishery.

Species	Year	Dates	Quota (t)	Trip Limit (t)
English sole	1990	Annual	700	-
English sole	1991	Annual	850	-
English sole	1992	Annual	850	-
English sole	1993	Annual	850	-
English sole	1994	Annual	850	-
English sole	1995	Annual	1050	-
English sole	1996	Annual	500	-
English sole	1997	Annual	600	-
English sole	1998	Annual	600	-
English sole	1999	Annual	600	-
English sole	2000	Annual	600	-
Rock sole	1985	Annual	no quota	14
Rock sole	1986	Annual	no quota	14
Rock sole	1987	Annual	no quota	14
Rock sole	1988	Annual	no quota	14
Rock sole	1993	Annual	1150	9
Rock sole	1994	Annual	1500	-
Rock sole	1995	Annual	1525	-
Rock sole	1996	Annual	1000	-
Rock sole	1997	Annual	1100	-
Rock sole	1998	Annual	1100	-
Rock sole	1999	Annual	1100	-
Rock sole	2000	Annual	1100	-

Table 6. Results of Pauly's method of estimation of M from life history characteristics.

Species	Sex	L_∞	K	T (Celsius)	M
English sole	Male	39.9	0.347	7.0	0.43
English sole	Female	49.4	0.275	7.0	0.35
Rock sole	Male	40.6	0.296	7.0	0.39
Rock sole	Female	50.5	0.207	7.0	0.29

Table 7. Total weight of rock sole by year and sex from port samples, 1945 to 2000.

Year	Males (kg)	Females (kg)	Proportion males
1945	81.8	542.9	0.131
1946	578.8	1656.9	0.259
1947	633.5	1370.6	0.316
1948	616.2	1851.4	0.250
1949	528.6	1423.1	0.271
1950	539.4	1392.3	0.279
1951	366.4	975.9	0.273
1952	1185.1	2085.5	0.362
1953	699.1	1661.1	0.296
1954	630.8	1420.8	0.307
1955	235.1	868.6	0.213
1956	754.4	1777.6	0.298
1957	1311.4	4313.3	0.233
1958	1058.0	5305.6	0.166
1959	316.8	1391.9	0.185
1960	333.8	2071.1	0.139
1961	371.0	1117.6	0.249
1962	250.1	1789.5	0.123
1963	353.5	1734.7	0.169
1964	492.3	3646.5	0.119
1965	349.0	2256.9	0.134
1966	1227.2	6599.1	0.157
1967	816.7	4802.0	0.145
1968	640.7	4603.5	0.122
1969	551.4	3079.0	0.152
1970	316.3	1837.6	0.147
1971	283.4	1973.4	0.126
1972	151.0	625.2	0.195
1973	275.4	2052.6	0.118
1974	210.2	1226.2	0.146
1975	199.8	806.4	0.199
1976	302.1	1468.3	0.171
1977	920.2	4342.2	0.175
1978	427.7	2638.7	0.139
1979	199.7	684.4	0.226
1980	240.7	1878.8	0.114
1981	92.3	241.7	0.276
1982	133.3	378.4	0.260
1983	110.3	453.8	0.196
1984	91.7	276.6	0.249
1985	111.0	807.1	0.121
1986	274.2	1728.4	0.137
1987	78.5	687.5	0.102
1988	177.6	1062.5	0.143
1989	136.0	760.8	0.152
1990	106.9	587.5	0.154
1991	131.9	741.8	0.151
1992	97.0	580.8	0.143
1993	32.6	247.3	0.116
1994	98.8	641.6	0.133
1995	84.3	731.7	0.103
1996	206.7	1054.5	0.164
1997	36.1	250.0	0.126
1998	145.0	598.7	0.195
1999	45.7	555.9	0.076
2000	16.7	137.8	0.108

Table 8. Total weight of English sole by year and sex from port samples, 1944 to 2000.

Year	Males (kg)	Females (kg)	Proportion Males
1944	152.0	249.5	0.379
1945	303.9	379.2	0.445
1946	486.3	648.2	0.429
1947	355.2	428.6	0.453
1948	778.1	1197.5	0.394
1949	913.5	929.9	0.496
1950	2034.9	2621.8	0.437
1951	830.9	1023.8	0.448
1952	955.3	1346.7	0.415
1953	405.0	1809.0	0.183
1954	435.0	1183.0	0.269
1955	103.8	380.7	0.214
1956	615.0	2618.8	0.190
1957	505.7	1842.3	0.215
1958	768.1	2867.0	0.211
1959	532.2	2315.4	0.187
1960	591.4	2216.4	0.211
1961	804.1	3053.9	0.208
1962	343.9	859.3	0.286
1963	382.6	1220.1	0.239
1964	321.4	1122.6	0.223
1965	221.7	1358.6	0.140
1966	92.0	833.9	0.099
1967	128.9	937.3	0.121
1968	134.5	507.0	0.210
1969	303.8	1041.1	0.226
1970	304.0	906.8	0.251
1971	207.2	316.9	0.395
1972	46.8	164.8	0.221
1973	123.6	373.0	0.249
1974	57.5	219.2	0.208
1975	168.0	466.8	0.265
1976	138.9	537.4	0.205
1977	531.7	1215.7	0.304
1978	366.9	785.4	0.318
1979	662.4	1124.8	0.371
1980	495.1	670.3	0.425
1981	52.3	162.6	0.243
1982	168.0	654.6	0.204
1983	113.5	617.9	0.155
1984	47.9	699.9	0.064
1985	154.6	722.6	0.176
1986	6.2	226.0	0.027
1987	5.8	150.3	0.037
1988	39.7	288.3	0.121
1989	9.2	64.3	0.125
1990	23.3	350.6	0.062
1991	15.9	202.4	0.073
1992	31.7	277.3	0.103
1993	27.1	287.3	0.086
1994	44.2	324.7	0.120
1995	63.3	726.2	0.080
1996	47.7	668.8	0.067
1997	19.7	368.0	0.051
1998	48.1	258.3	0.157
1999	25.6	198.8	0.114
2000	16.9	124.1	0.120

Table 9. Equilibrium reference point values for rock and English soles using various parameters sets $(\phi, B_0, \gamma, \delta, r, w_r, \lambda, \kappa)$ to compute the reference points defined in Appendix B. Two assumptions regarding natural mortality, M=(0.2, 0.3), correspond to values of $\delta = (0.181, 0.259)$. Beverton-Holt and Ricker stock recruitment curves are denoted by $\gamma = -1$ and $\gamma = 0$, respectively. The biomass is scaled to a fixed carrying capacity $B_0 = 10$ thousand tonnes. Values of $h_{0.1}$ and $C_{0.1}$ correspond to estimates of $F_{0.1}$ estimated from yield per recruit analysis.

Parameter	English Sole				Rock sole			
γ	-1.000	0.000	-1.000	0.000	-1.000	0.000	-1.000	0.000
r	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
ϕ	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
B_0	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000
δ	0.181	0.181	0.259	0.259	0.181	0.181	0.259	0.259
w_r	0.378	0.378	0.378	0.378	0.508	0.508	0.508	0.508
λ	0.077	0.077	0.077	0.077	0.155	0.155	0.155	0.155
κ	0.984	0.984	0.984	0.984	0.941	0.941	0.941	0.941
$h^{\#}$	0.308	0.308	0.417	0.417	0.307	0.307	0.410	0.410
$F^{\#}$	0.368	0.368	0.540	0.540	0.367	0.367	0.528	0.528
h^{*}	0.122	0.159	0.182	0.232	0.123	0.159	0.178	0.227
F^{*}	0.130	0.173	0.201	0.264	0.131	0.173	0.196	0.257
C^{*}	0.455	0.763	0.711	1.200	0.462	0.772	0.702	1.180
B^{*}	3.727	4.796	3.908	5.174	3.758	4.857	3.943	5.199
A^{*}	11.557	11.211	10.538	10.320	11.546	11.211	10.557	10.340
W^{*}	0.552	0.530	0.484	0.470	0.786	0.753	0.687	0.664
$h_{50\%}$	0.107	0.107	0.158	0.158	0.109	0.109	0.156	0.156
$C_{50\%}$	0.450	0.683	0.702	1.067	0.459	0.696	0.694	1.053
$h_{60\%}$	0.075	0.075	0.112	0.112	0.077	0.077	0.111	0.111
$C_{60\%}$	0.406	0.554	0.631	0.861	0.416	0.569	0.625	0.853
$F_{0.1}$	0.220	0.220	0.220	0.220	0.210	0.210	0.210	0.210
$h_{0.1}$	0.197	0.197	0.197	0.197	0.189	0.189	0.189	0.189
$C_{0.1}$	0.368	0.717	0.708	1.170	0.391	0.744	0.700	1.143

Table 10. Rock sole catch-age model results for four cases specified by values of the parameters (Δ, M). Values in bold were fixed in the analysis.

Parameter	Case 1	Case 2	Case 3	Case 4
Δ	**0.0**	-0.107667	-0.097063	-0.103535
M	**0.2**	**0.2**	**0.3**	0.246387
α	4.8515	4.73074	3.95665	4.3898
β_1	0.245724	0.249119	0.207365	0.230164
q	7.90882	7.95461	5.91342	7.01114
R	0.469248	0.497407	1.08796	0.718059
γ	0.970223	0.970363	0.958821	0.965353
ρ	**0.7**	**0.7**	**0.7**	**0.7**
κ^2	0.201007	0.197093	0.187142	0.191037
σ_1	0.375107	0.371437	0.361938	0.365686
τ_1	0.245565	0.243162	0.236944	0.239397
τ_2	0.650074	0.650827	0.655715	0.653066
F_{1999}	0.152946	0.148589	0.125375	0.139471
B_{1999}	2.95136	3.03144	3.55221	3.2153
S_{1999}	2.93894	3.06469	3.68017	3.28034
D_{1999}	0.418572	0.418572	0.418572	0.418572
$-\ln L$	-17.098	-17.4749	-17.4518	-17.7271
$-\ln L_1$	-37.5761	-38.7712	-42.2222	-40.6489
$-\ln L_2$	1.96669	2.47583	3.95201	3.18444
$-\ln L_3$	18.5114	18.8204	20.8184	19.7374

Table 11. English sole catch-age model results for four cases specified by values of the parameters (Δ, M). Values in bold were fixed in the analysis.

Parameter	Case 1	Case 2	Case 3	Case 4
Δ	**0.0**	-0.243212	-0.211540	-0.127260
M	**0.2**	**0.2**	**0.3**	0.483133
α	4.38945	4.10355	3.6688	2.16865
β_1	0.34441	0.353352	0.304067	0.180369
q	29.7281	30.5962	20.5038	5.4657
R	0.380182	0.483747	1.28702	7.27522
γ	0.976975	0.978743	0.962578	0.949923
ρ	**0.7**	**0.7**	**0.7**	**0.7**
κ^2	0.173274	0.15616	0.140496	0.131965
σ_1	0.34827	0.330624	0.313604	0.303933
τ_1	0.227996	0.216444	0.205302	0.198971
τ_2	0.391878	0.389555	0.388097	0.384855
F_{1999}	0.210979	0.187061	0.129775	0.036111
B_{1999}	1.71416	1.91111	2.67896	9.19289
S_{1999}	1.81652	2.24767	3.28575	14.0862
D_{1999}	0.326048	0.326048	0.326048	0.326048
$-\ln L$	-205.036	-210.917	-216.355	-221.866
$-\ln L_1$	-39.5523	-43.3768	-48.4191	-51.3521
$-\ln L_2$	-1.68138	-1.50906	-0.49785	0.068831
$-\ln L_3$	-163.802	-166.032	-167.438	-170.583

Table 12. Summary of stock assessments for rock sole and English sole conducted by Walters and Bonfil (1999). Biomass estimates derived from swept area expansion of 1996 observer data are indicated by Method A. Estimates obtained from a delay difference model using historical catch rate data are indicated by Method B.

Method	Quantity	Rock sole	English sole
A	Min. biomass (t) – ground 1	573	1318
A	Min. biomass (t) – ground 2	1654	828
A	Min. biomass (t) – total	2227	2146
B	Ratio B_{1996}/B_0 - ground 1	0.39	0.72
B	Ratio B_{1996}/B_0 - ground 2	1.01	0.88
B	Min. coastwide MSY (t)	1391	1679
B	Most probable coastwide MSY (t)	681	1003

Table 13. Estimated habitat area and biomass for rock sole and English sole for Hecate Strait (Major areas 5C/D). Available area A is determined from bathymetric data while area A^* is derived from the commercial fishing locations (1996 to 2000) that captured the given species. Biomasses B and B^* correspond to estimates derived using A and A^*, respectively, using fish densities obtained from the indicated data source. For commercial data, biomass estimates represent the mean of quarterly estimates (1996 to 1999) obtained with 10 percent trimming as described by Schnute and Haigh (2000, Table 5). Numbers in brackets indicate the lower and upper bounds of a 95 percent confidence limit obtained using the percentile method.

Symbol	Definition	Source	Rock sole	English sole
A	Available Area (km^2)	Bathymetry	29,843	29,710
A^*	Fished Area (km^2)	Commercial	2,056	2,555
B	1996-99 avg. biomass	Commercial	12.31	6.86
B^*	1996-99 avg. biomass	Commercial	0.85	0.59
B_{1998}	1998 biomass	Commercial	10.88 (9.83, 11.88)	5.96 (5.55, 6.57)
B_{1999}	1999 biomass	Commercial	11.28 (10.16, 12.26)	6.09 (5.63, 6.76)
B_{2000}	2000 biomass	Commercial	11.43 (10.38, 12.77)	6.01 (5.51, 7.08)
B_{1998}	1998 biomass	Survey	4.48 (2.46, 9.32)	6.15 (3.42, 18.8)
B_{2000}	2000 biomass	Survey	3.28 (2.14, 6.57)	7.44 (4.44, 12.14)

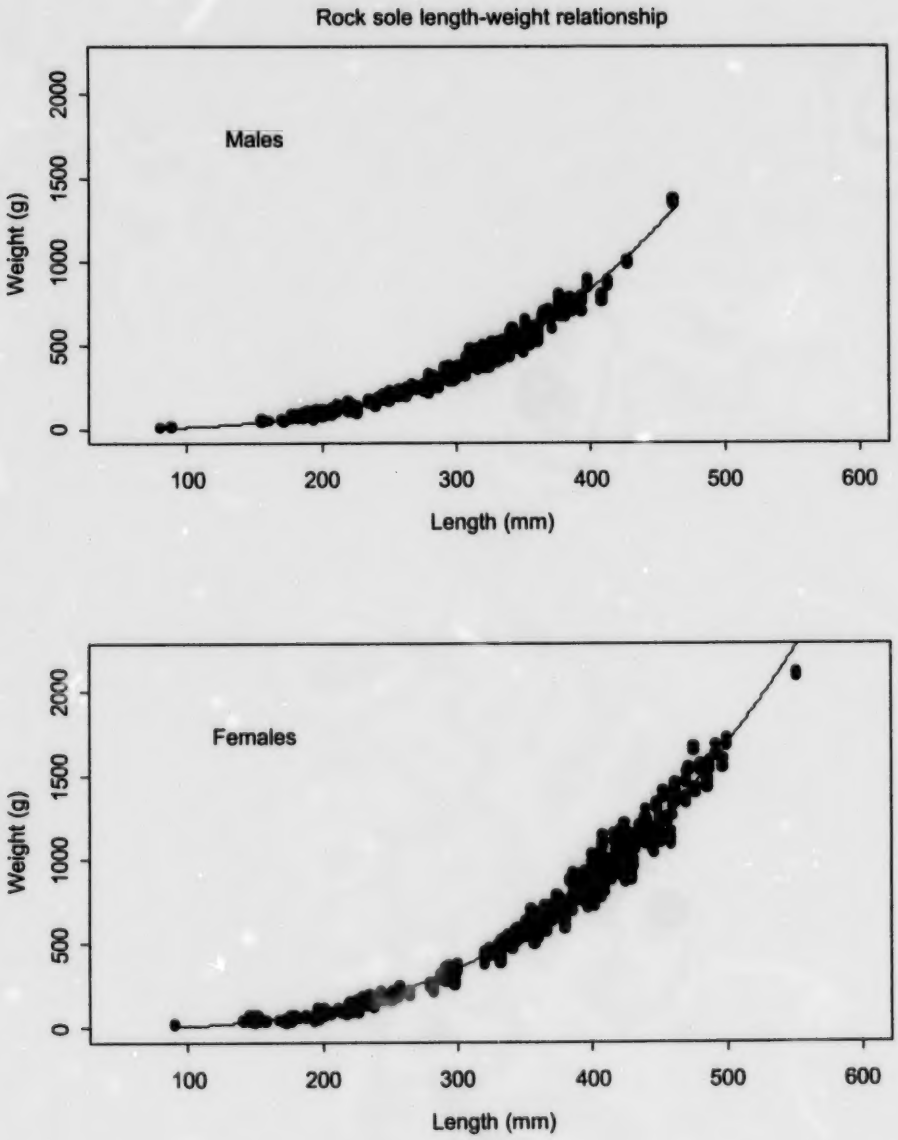

Figure 1. Length-weight relationships for Hecate Strait rock sole males and females. The data represent pooled commercial and survey samples from 1945 to1999.

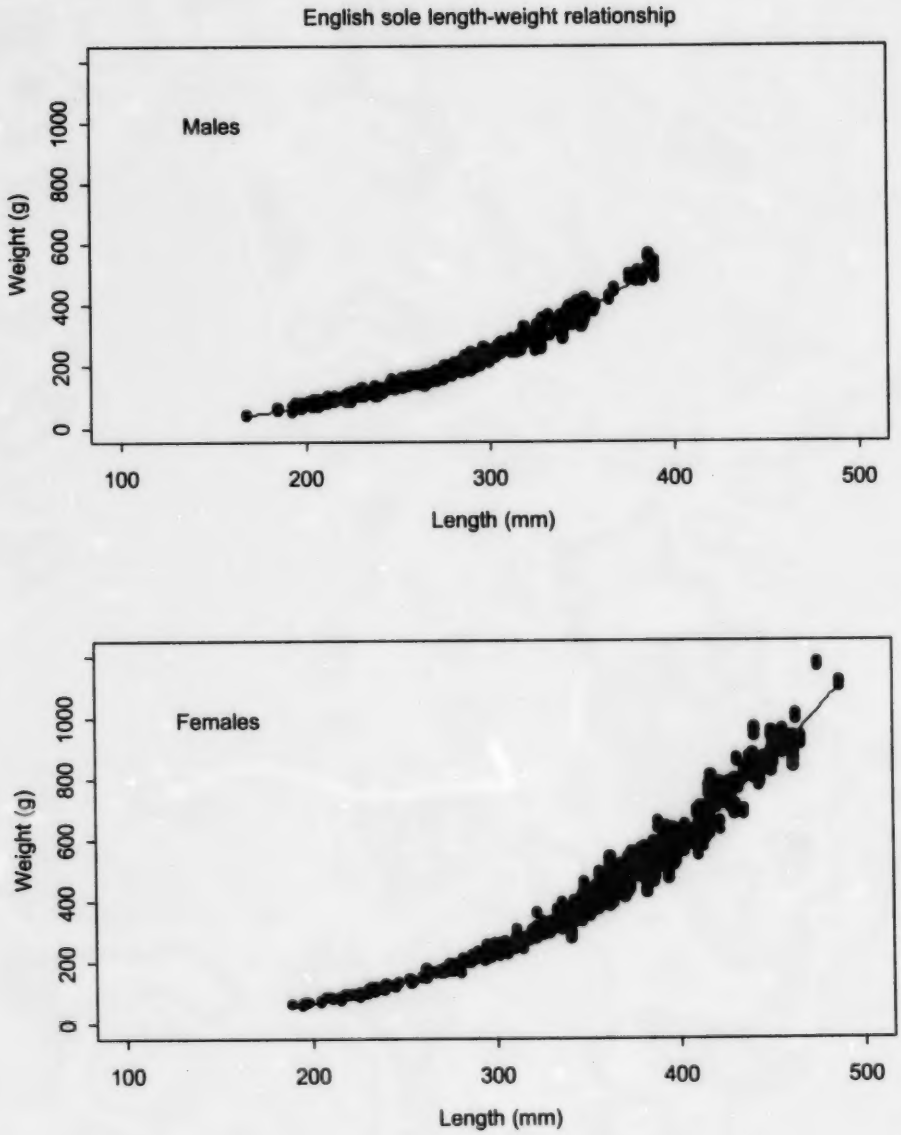

Figure 2. Length-weight relationships for Hecate Strait English sole males and females. The data represent pooled commercial and survey samples from 1953 to 1999.

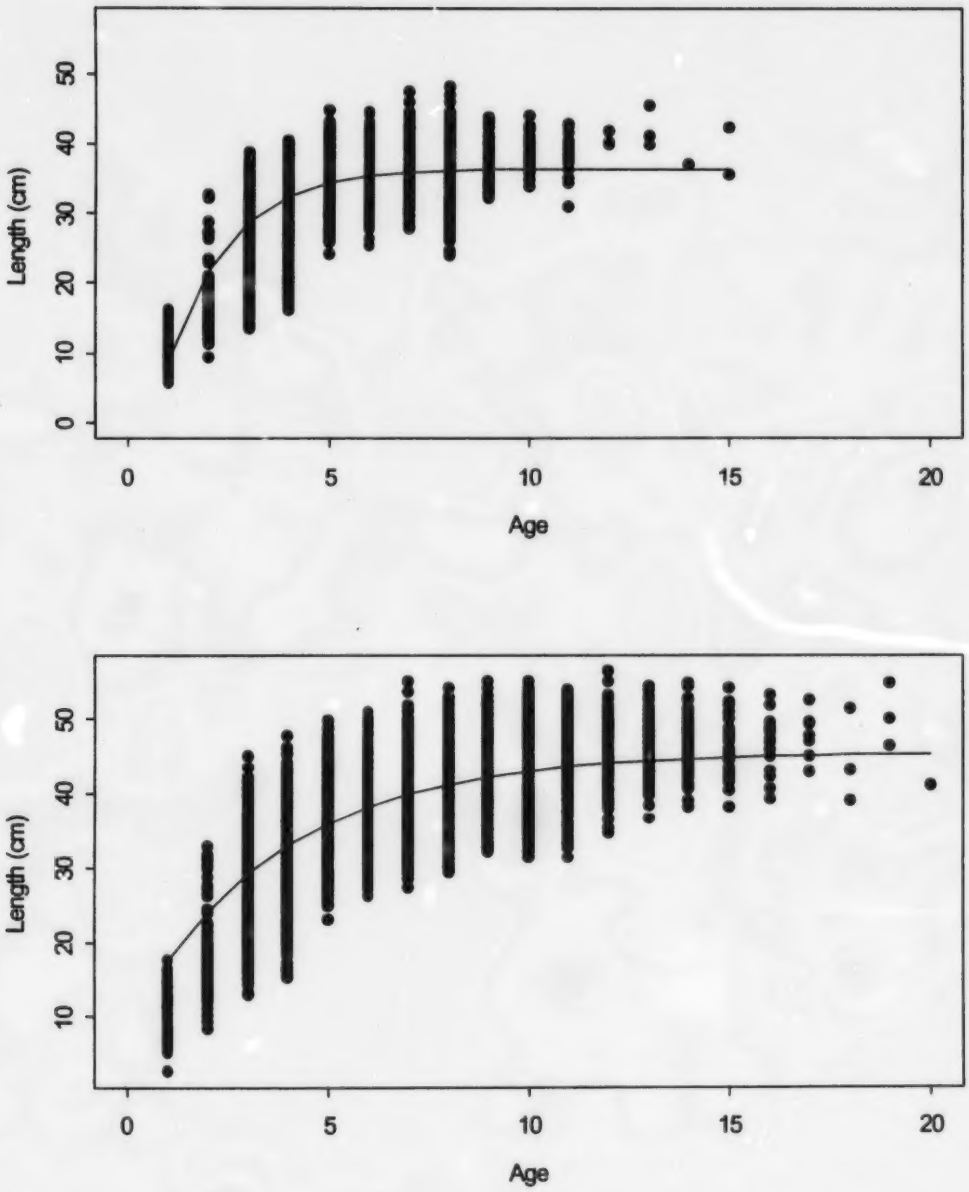

Figure 3. Length at age relationships for Hecate Strait rock sole males (upper panel) and females (lower panel). The data represent pooled commercial and survey data from 1945 to 1999.

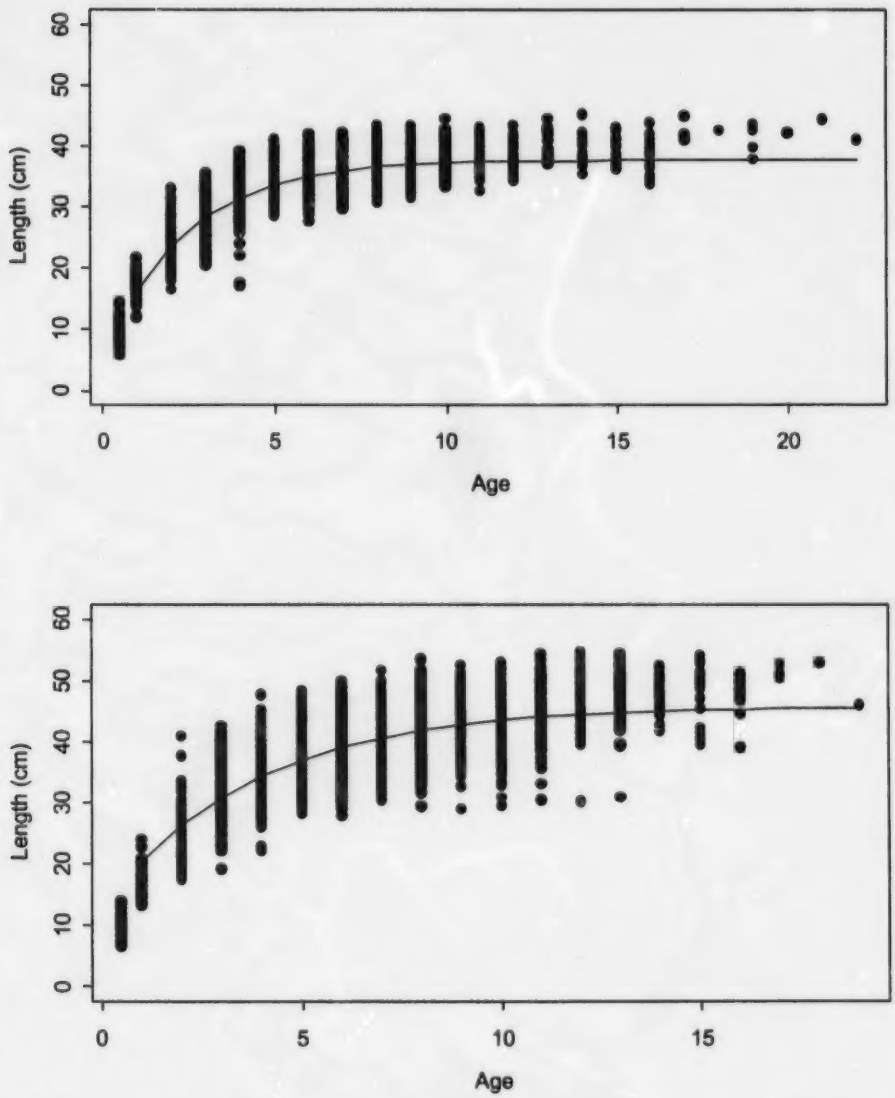

Figure 4. Length at age relationships for Hecate Strait English sole males (upper panel) and females (lower panel). The data represent pooled commercial and survey data from 1944 to 1999.

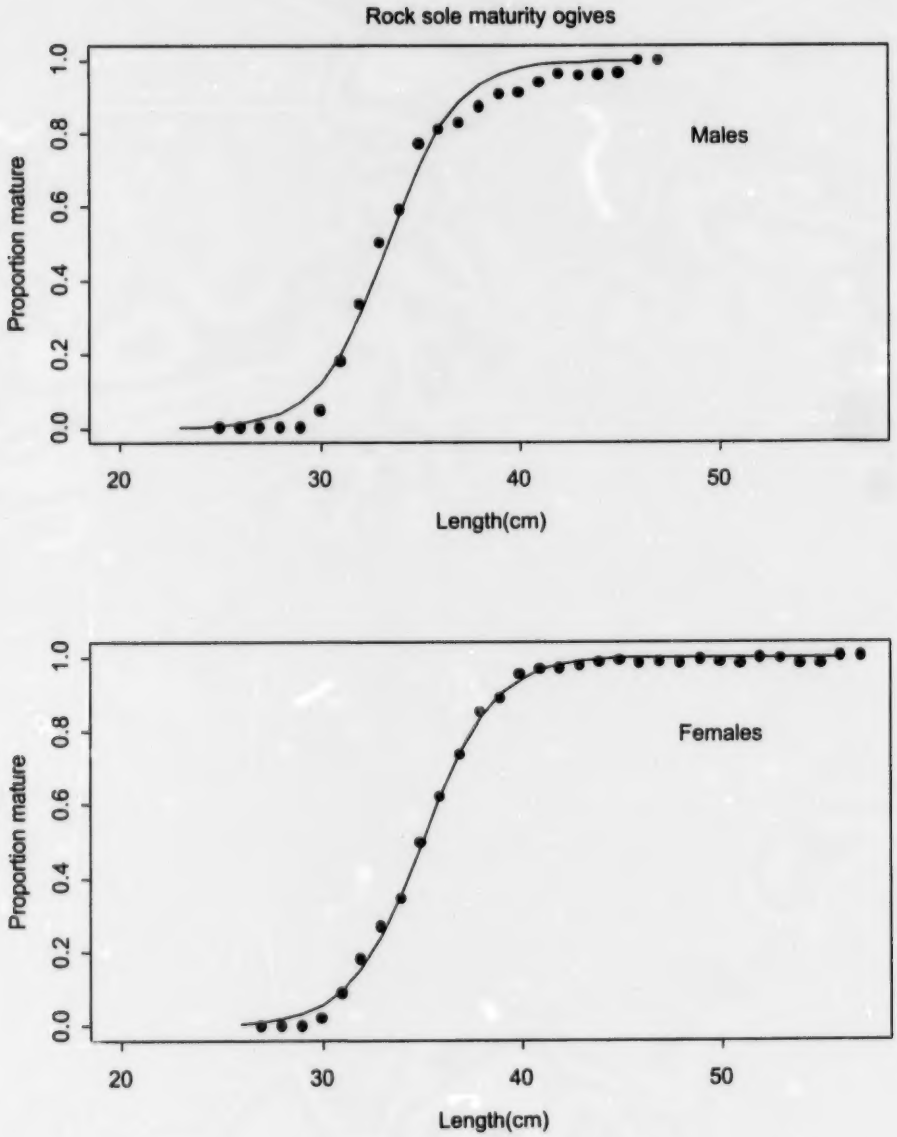

Figure 5. Maturity ogives for male and female rock sole. The length (cm) and maturity data represent pooled commercial and survey samples from 1945 to 1999.

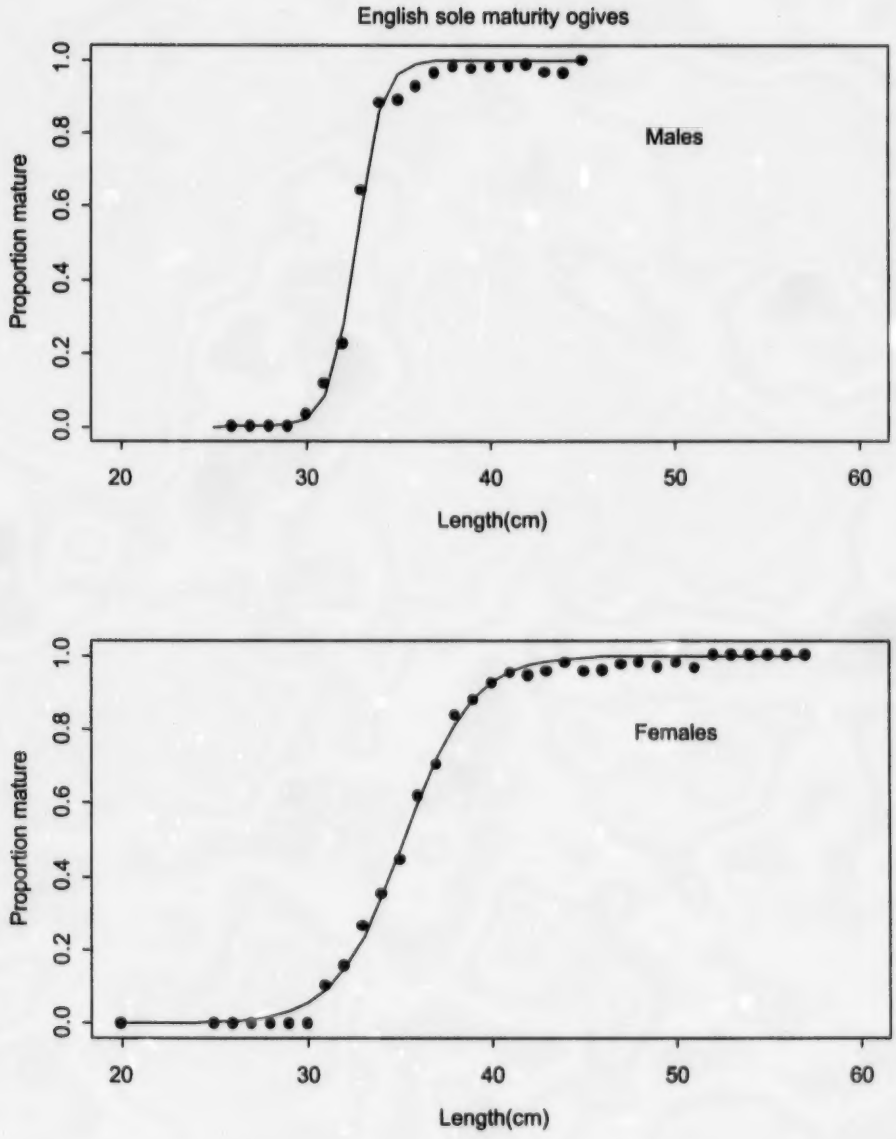

Figure 6. Maturity ogives for male and female English sole. The length (cm) and maturity data represent pooled commercial and survey samples from 1953 to 1999.

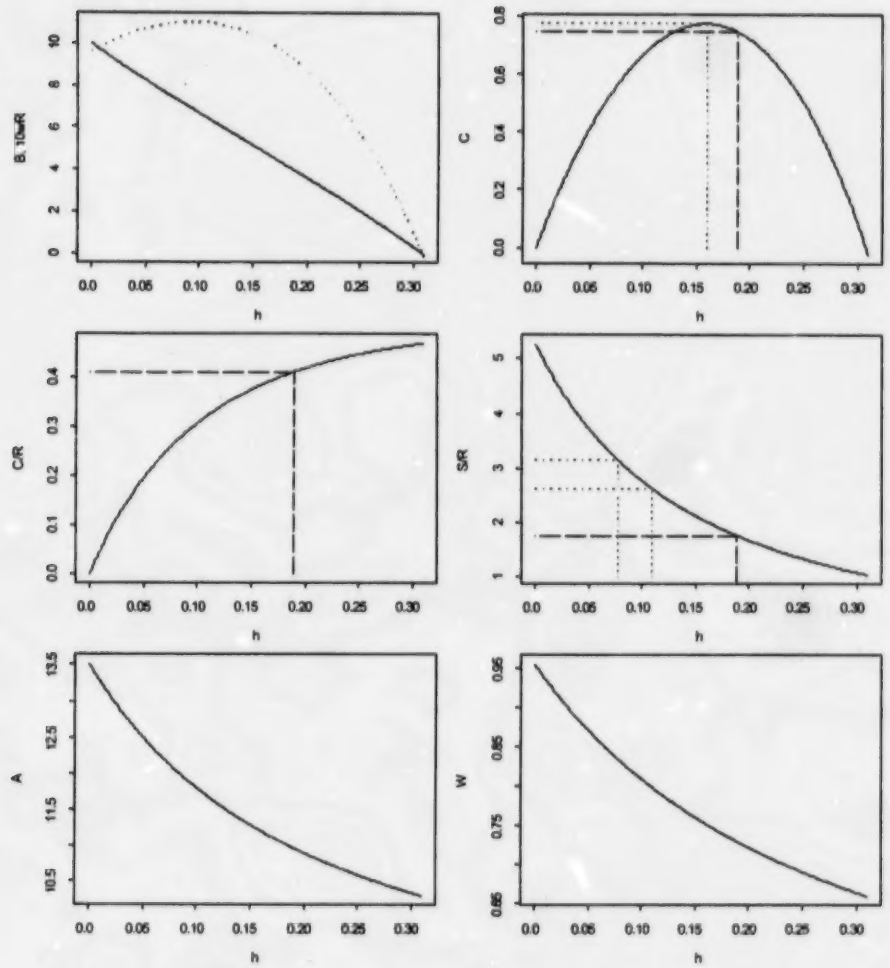

Figure 7. Target reference points for rock sole under the assumption of a Ricker spawner recruit relationship with M=0.2. Panels show equilibrium values of biomass B, catch C, yield per recruit C/R, spawner biomass per recruit S/R, age A, and weight W, plotted against harvest rate, h. The dotted line in the upper left panel indicates 10 times the recruitment biomass $(10w_r R)$. Dotted lines in the upper right panel show the MSY point (h^*, C^*). Dashed lines indicate $(h_{0.1}, C_{0.1})$, corresponding to the target reference point $F_{0.1}$. Similarly, $(h_{0.1}, C_{0.1}/R_{0.1})$ is indicated by dashed lines in the yield per recruit $(h, C/R)$ plot. Dotted lines in the $(h, S/R)$ plot indicate the points $(h_{50\%}, h_{60\%})$ where the spawner to recruit ratio is $(0.5\, S_0/R_0)$ and $(0.6\, S_0/R_0)$, respectively.

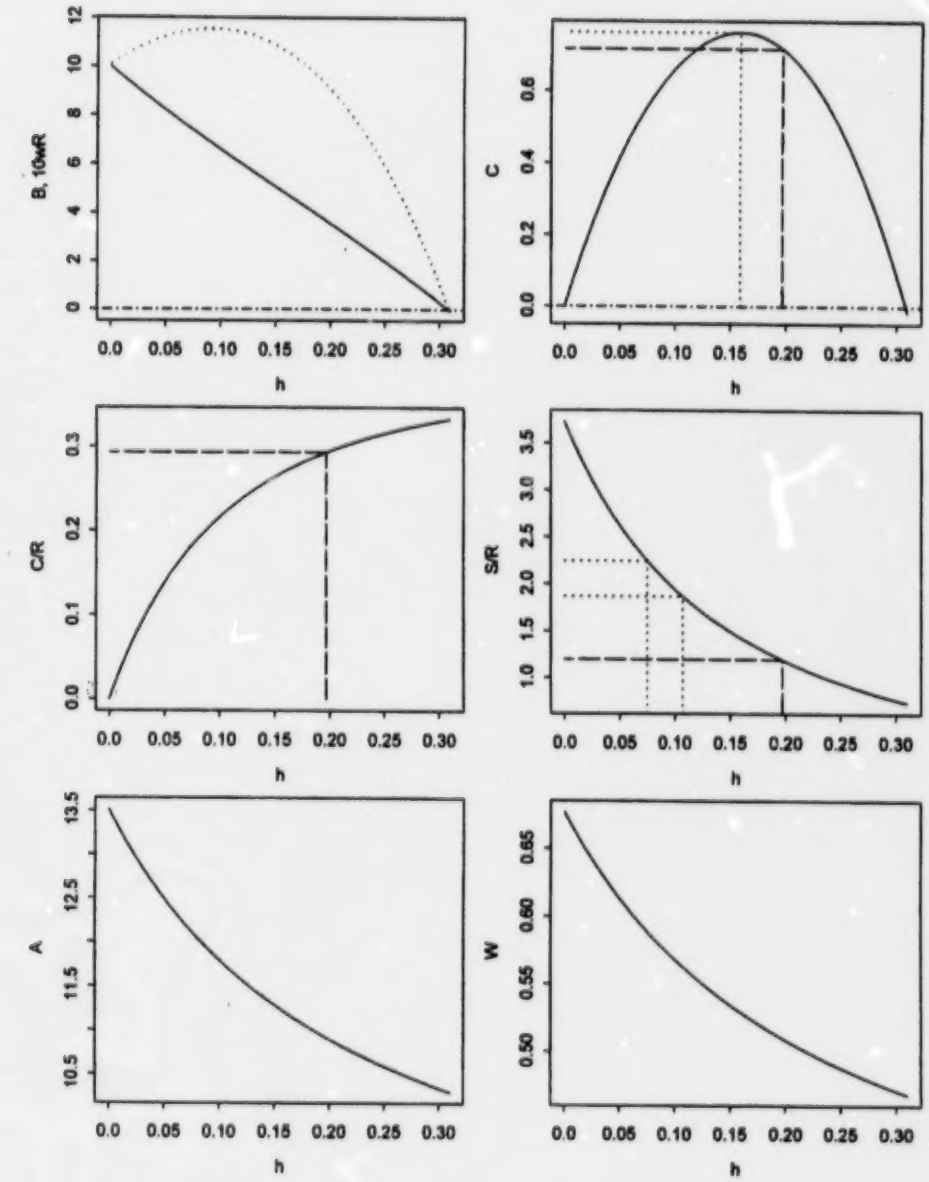

Figure 8. Target reference points for English sole under the assumption of a Ricker spawner recruit relationship with M=0.2. Panels as for Fig. 7.

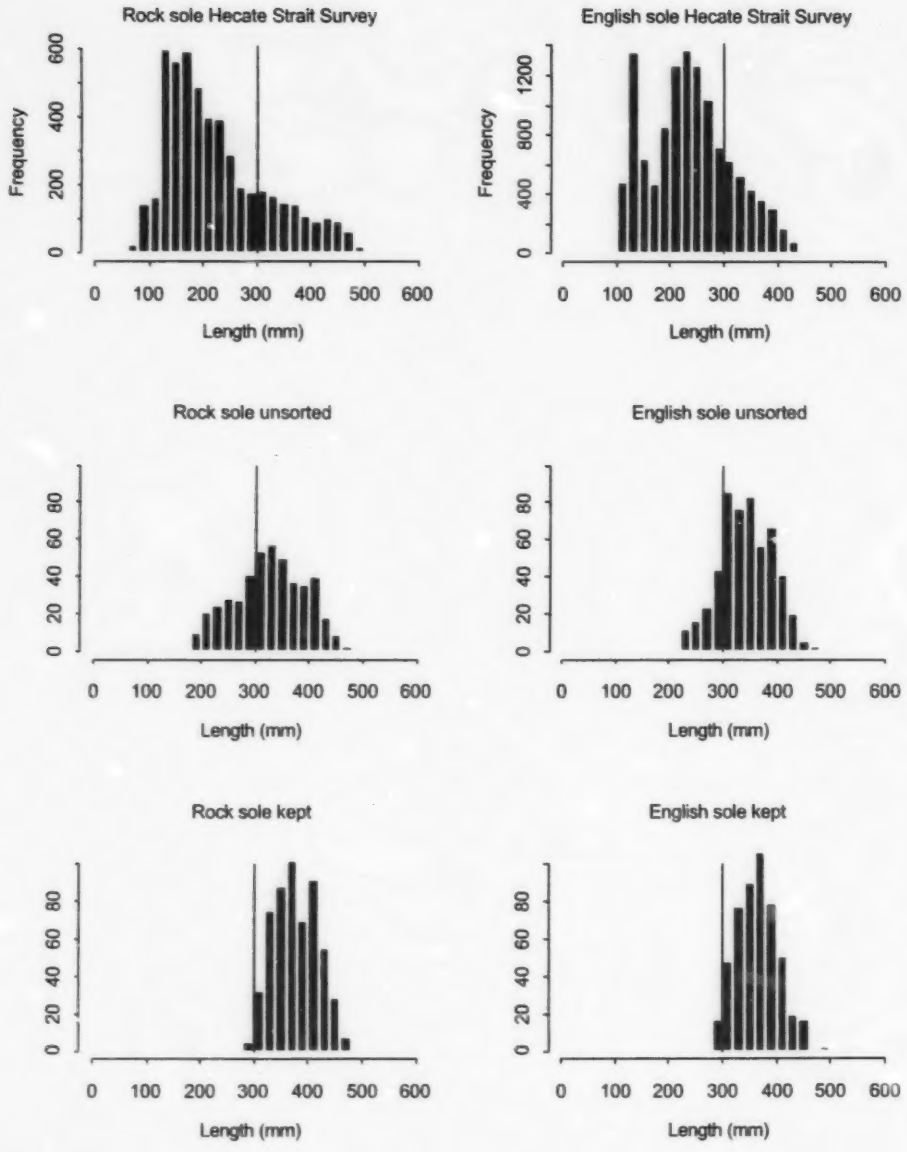
Rock sole Hecate Strait Survey
Frequency
0 200 400 600
0 100 200 300 400 500 600
Length (mm)
English sole Hecate Strait Survey
Frequency
0 400 800 1200
0 100 200 300 400 500 600
Length (mm)
Rock sole unsorted
0 20 40 60 80
0 100 200 300 400 500 600
Length (mm)
English sole unsorted
0 20 40 60 80
0 100 200 300 400 500 600
Length (mm)
Rock sole kept
0 20 40 60 80
0 100 200 300 400 500 600
Length (mm)
English sole kept
0 20 40 60 80
0 100 200 300 400 500 600
Length (mm)

Figure 9. Size composition of rock sole and English sole caught on the Hecate Strait assemblage survey and in the commercial fishery. The data from the commercial fishery include samples from the unsorted and the sorted (kept) catch. A vertical line indicates the minimum length (300 mm) of "adult" fish.

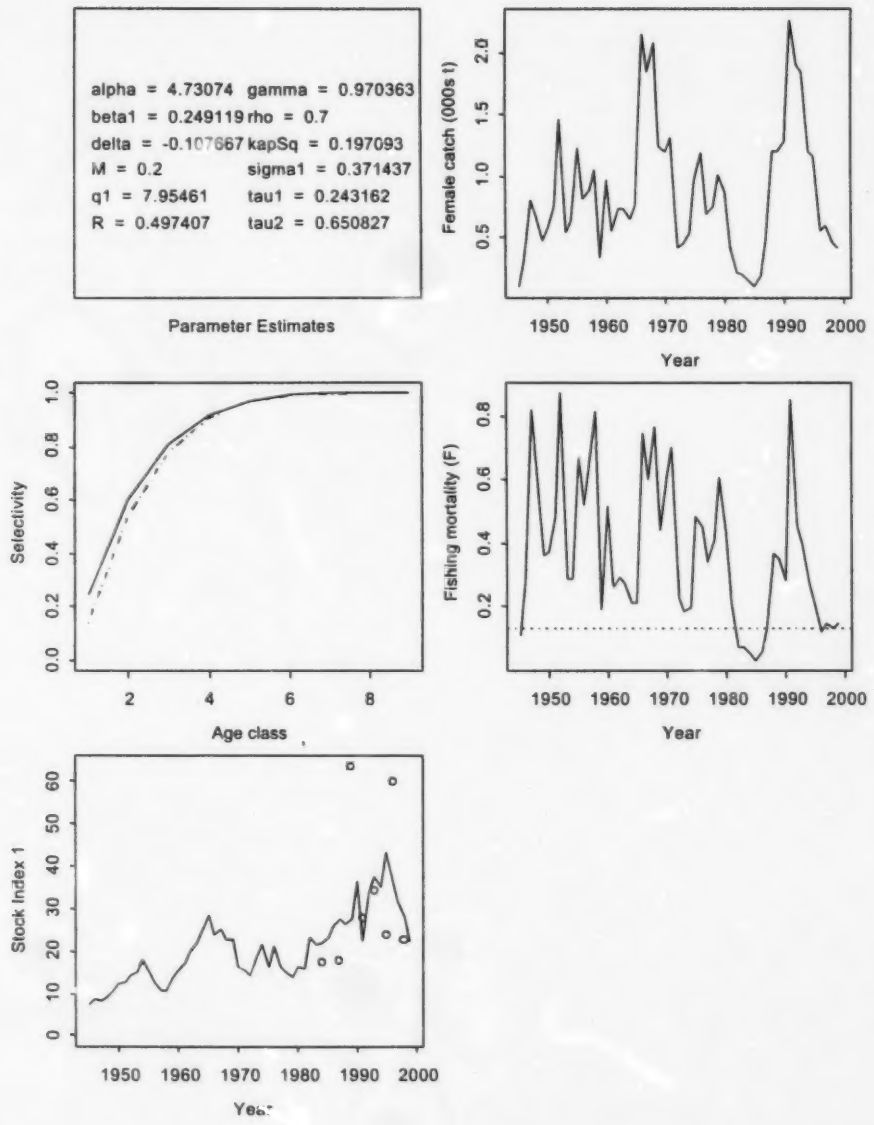

Figure 10. Catch-age model results for rock sole (Table 10, Case1). Pre-1996 selectivity (solid line) and selectivity after adoption of the mesh regulation in 1996 (dot-dash line) are shown in the middle left panel. The dotted line in the middle right panel is 2/3*M*. Observed (circles) and fitted (solid line) values of the stock index are shown in the bottom panel.

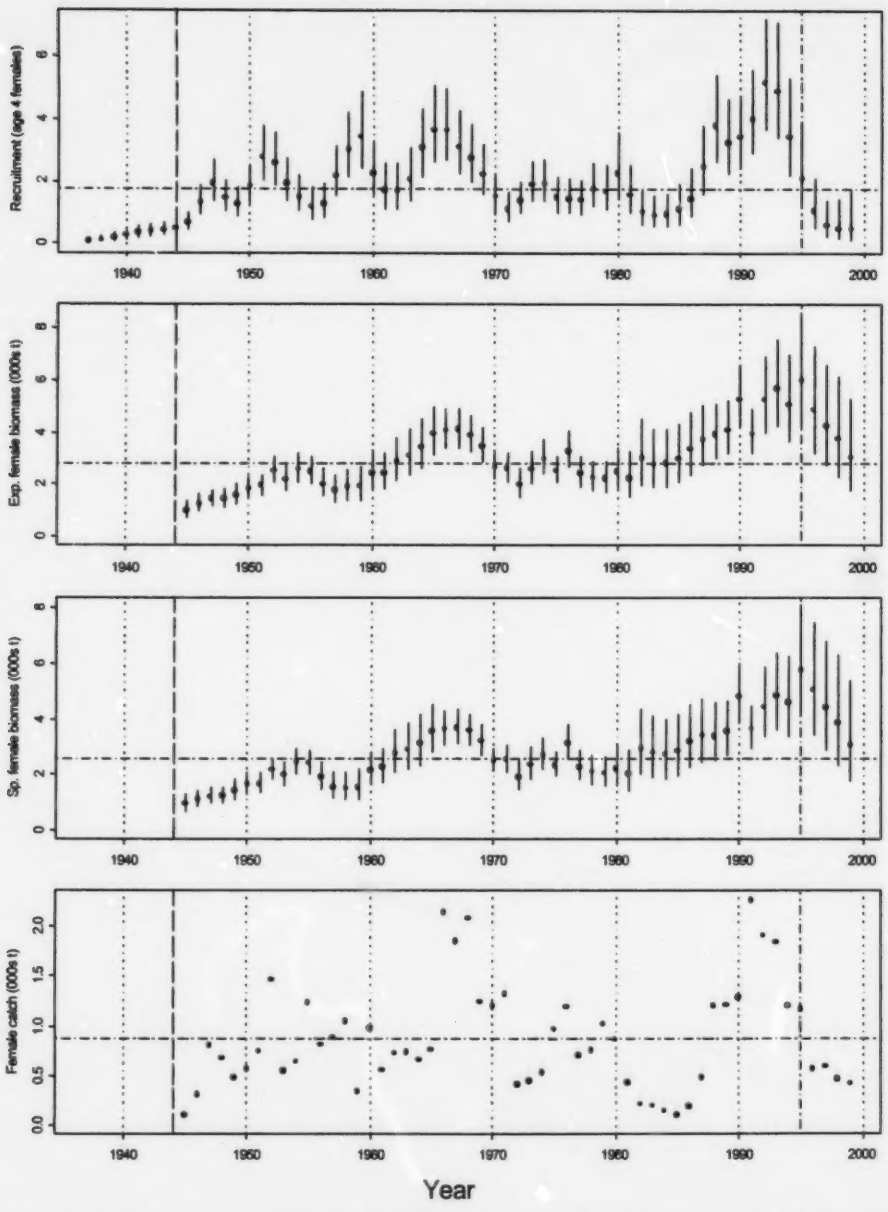

Figure 11. Recruitment, exploitable female biomass, spawning biomass, and female catch for rock sole (Table 10, Case 1). Vertical bars represent approximate pointwise 95% confidence intervals. The horizontal dot-dash line in each panel represents the mean value of the series from 1945 to 1999.

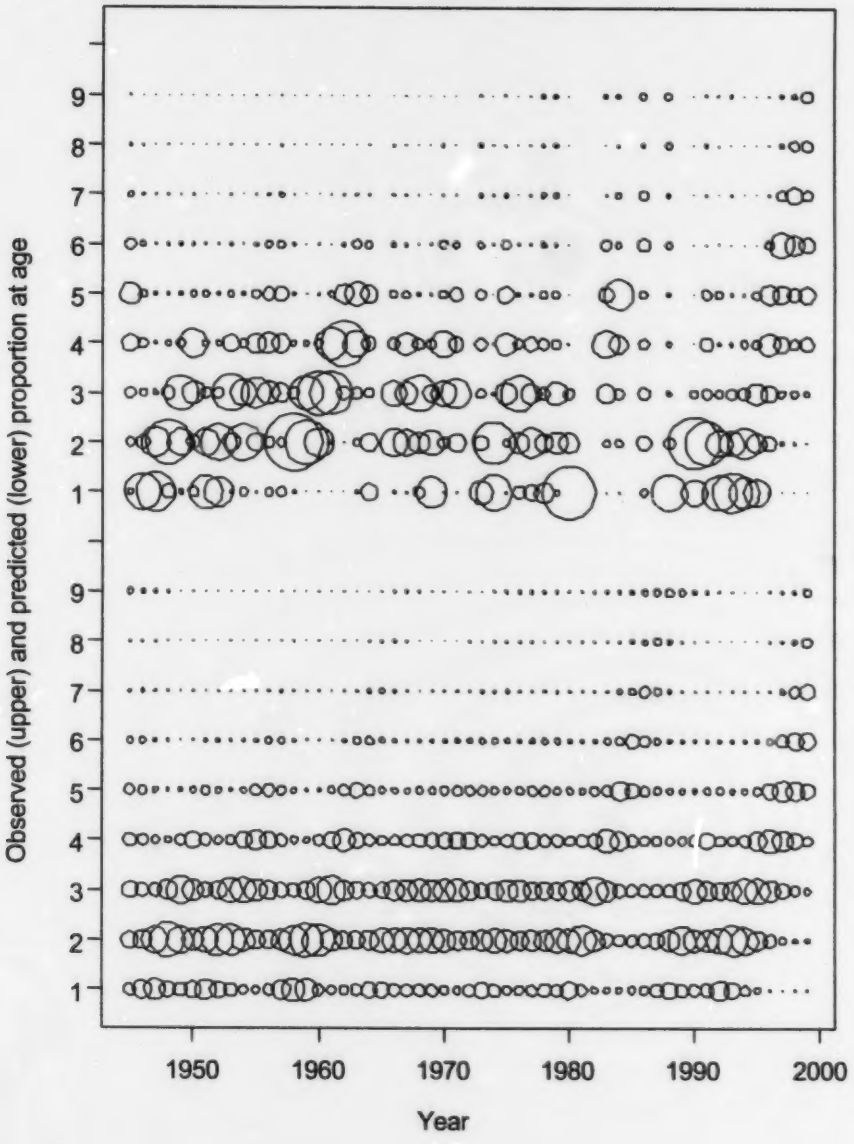

Figure 12. Observed and fitted proportions at age for rock sole (Table 10, Case 1).

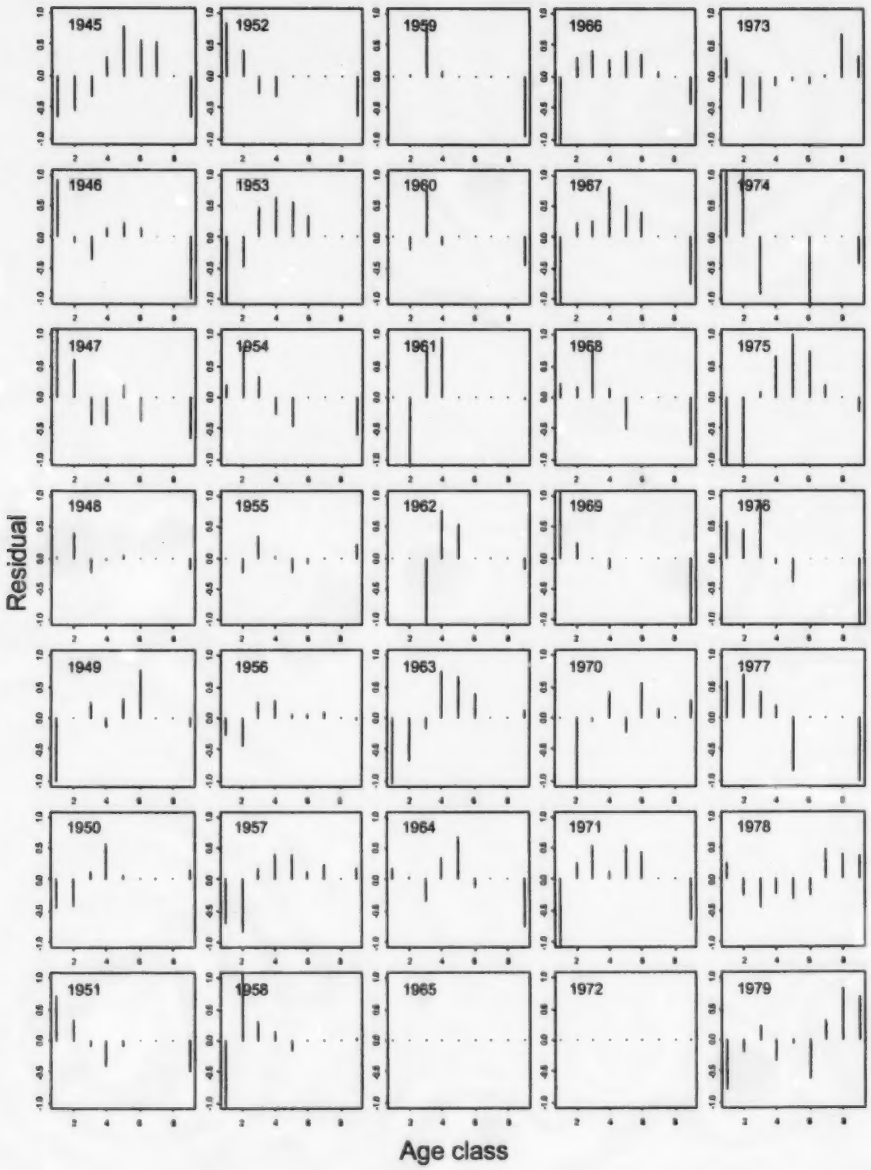

Figure 13. Residuals for proportions at age by year and age class for rock sole (Table 10, Case 1).

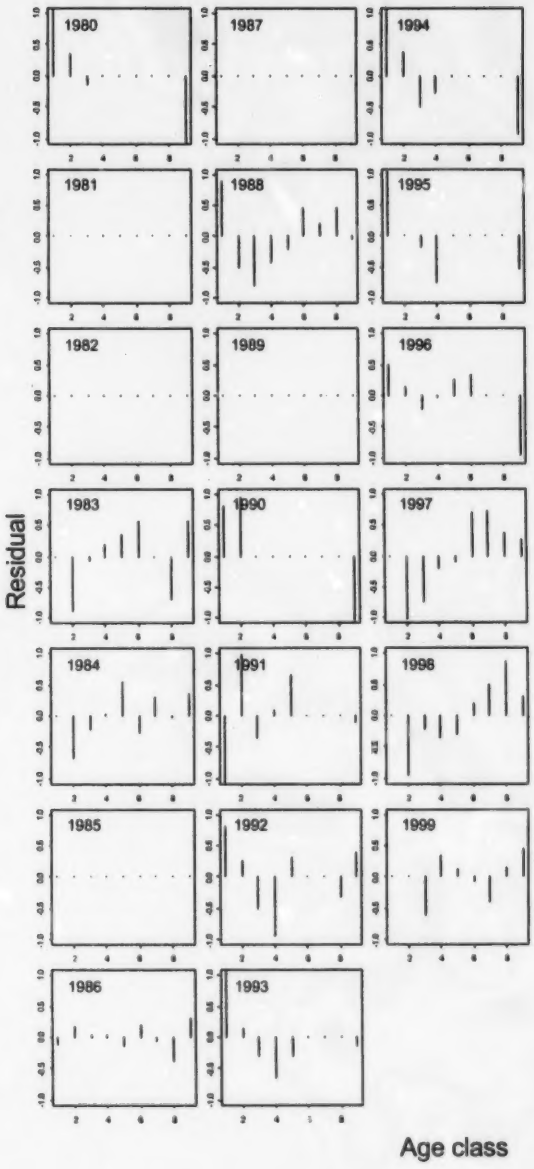

Figure 13 (cont'd).

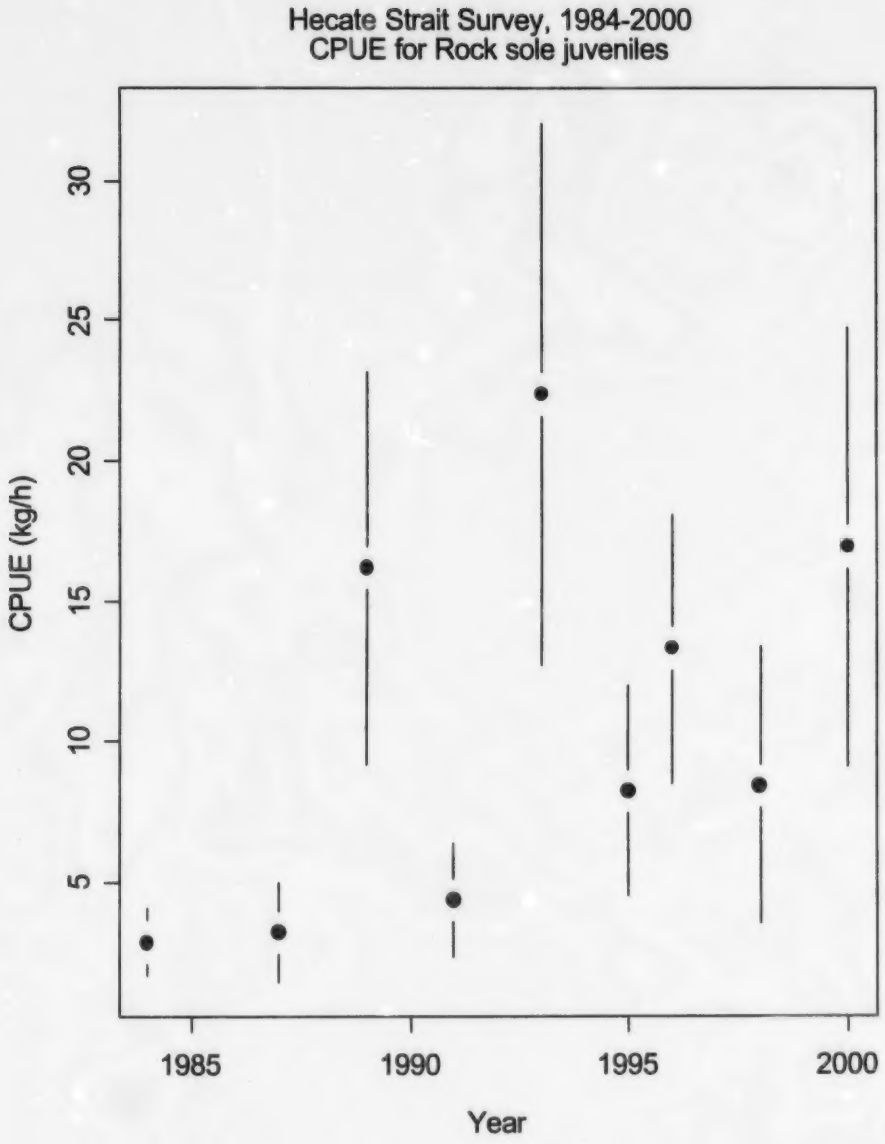

Figure 14. Mean annual catch per unit effort and 95% confidence intervals for juvenile (≤30 cm) rock sole caught on the Hecate Strait assemblage surveys, 1984 to 2000.

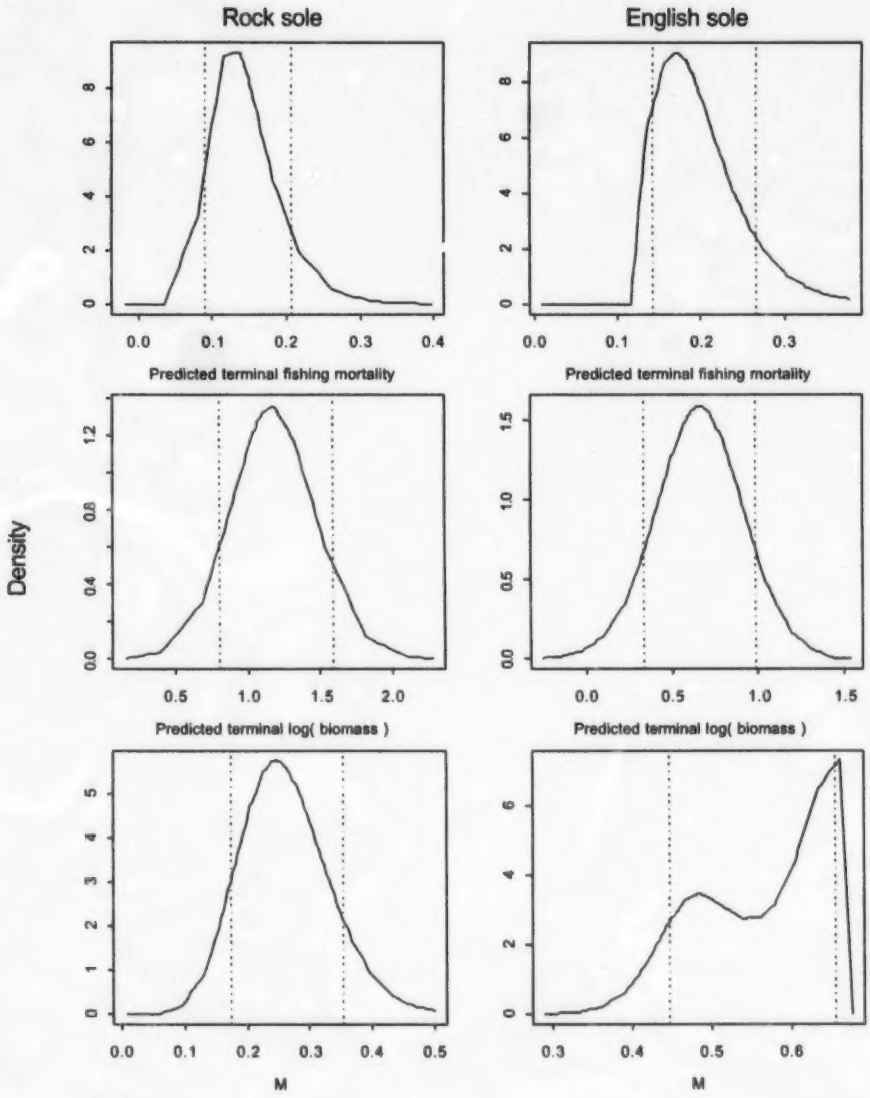

Figure 15. Approximate marginal Bayes probability distributions for parameters (F_{1999}, B_{1999}, M) for rock and English soles. The densities for F_{1999} and B_{1999} are computed for Case 2 (Tables 10 and 11). The densities for M are computed for Case 4 (Tables 10 and 11). Vertical dotted lines show where the probability is 0.9 that the parameter value exceeds (left), or is less than (right), the indicated point.

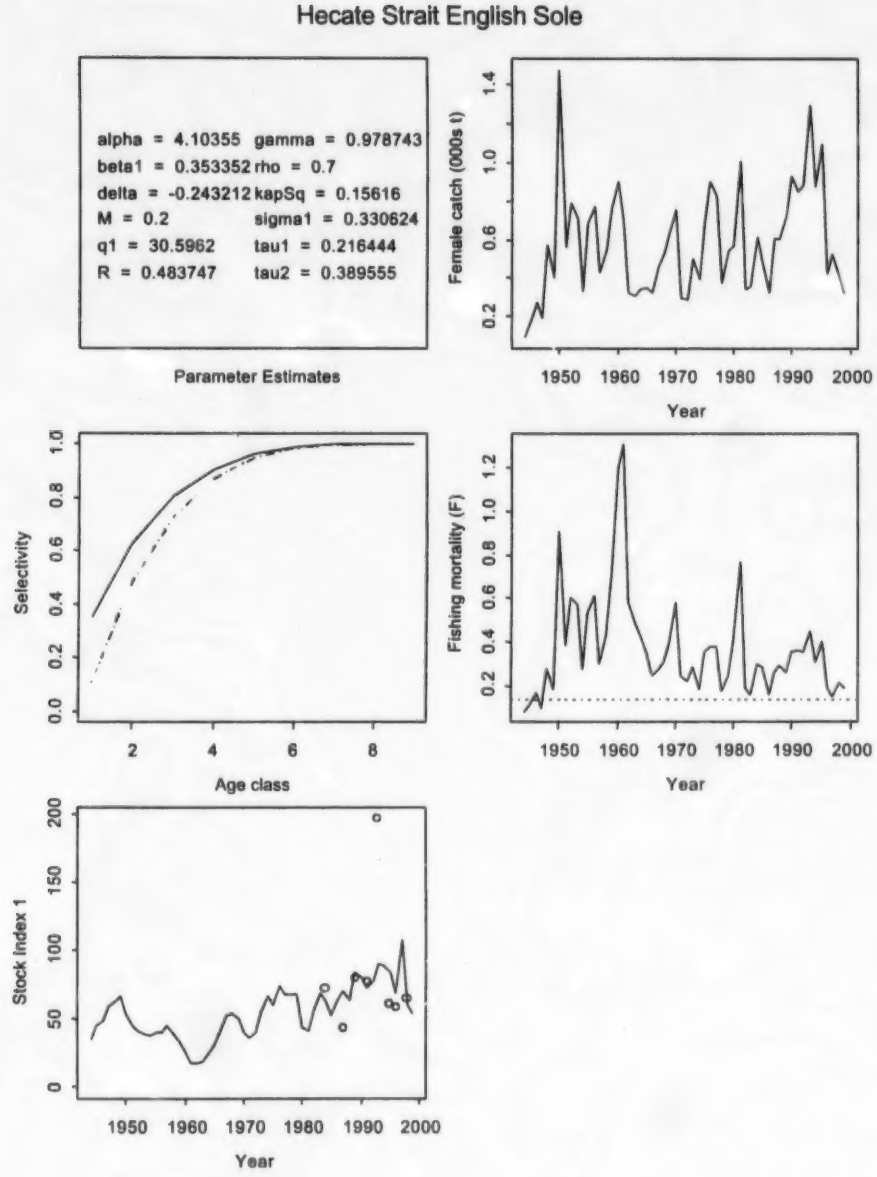

Figure 16. Catch-age model results for English sole (Table 11, Case1). Pre-1996 selectivity (solid line) and selectivity after adoption of the mesh regulation in 1996 (dot-dash line) are shown in the middle left panel. The dotted line in the middle right panel is 2/3*M*. Observed (circles) and fitted (solid line) values of the stock index are shown in the bottom panel.

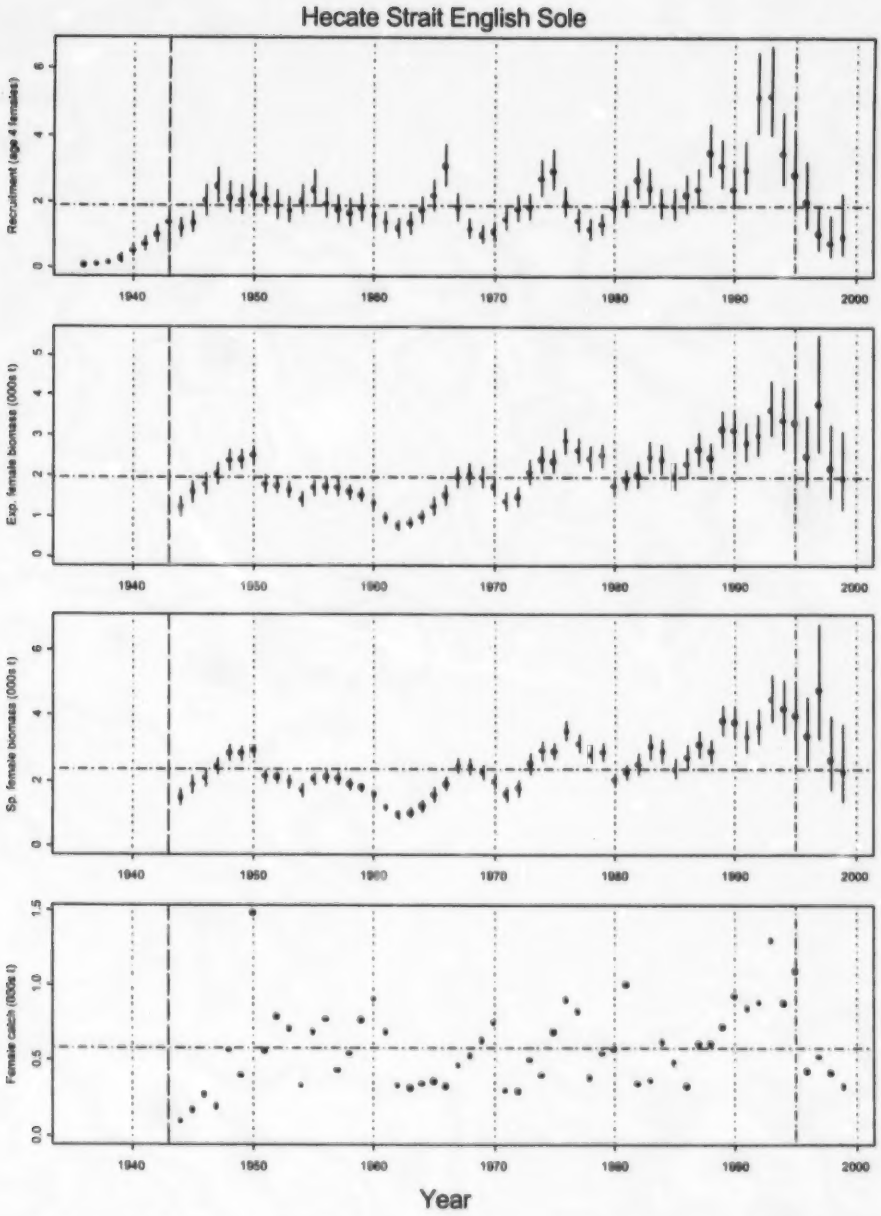

Figure 17. Recruitment, exploitable female biomass, spawning biomass, and female catch for English sole (Table 11, Case 1). Vertical bars represent approximate pointwise 95% confidence intervals. The horizontal dot-dash line in each panel represents the mean value of the series from 1944 to 1999.

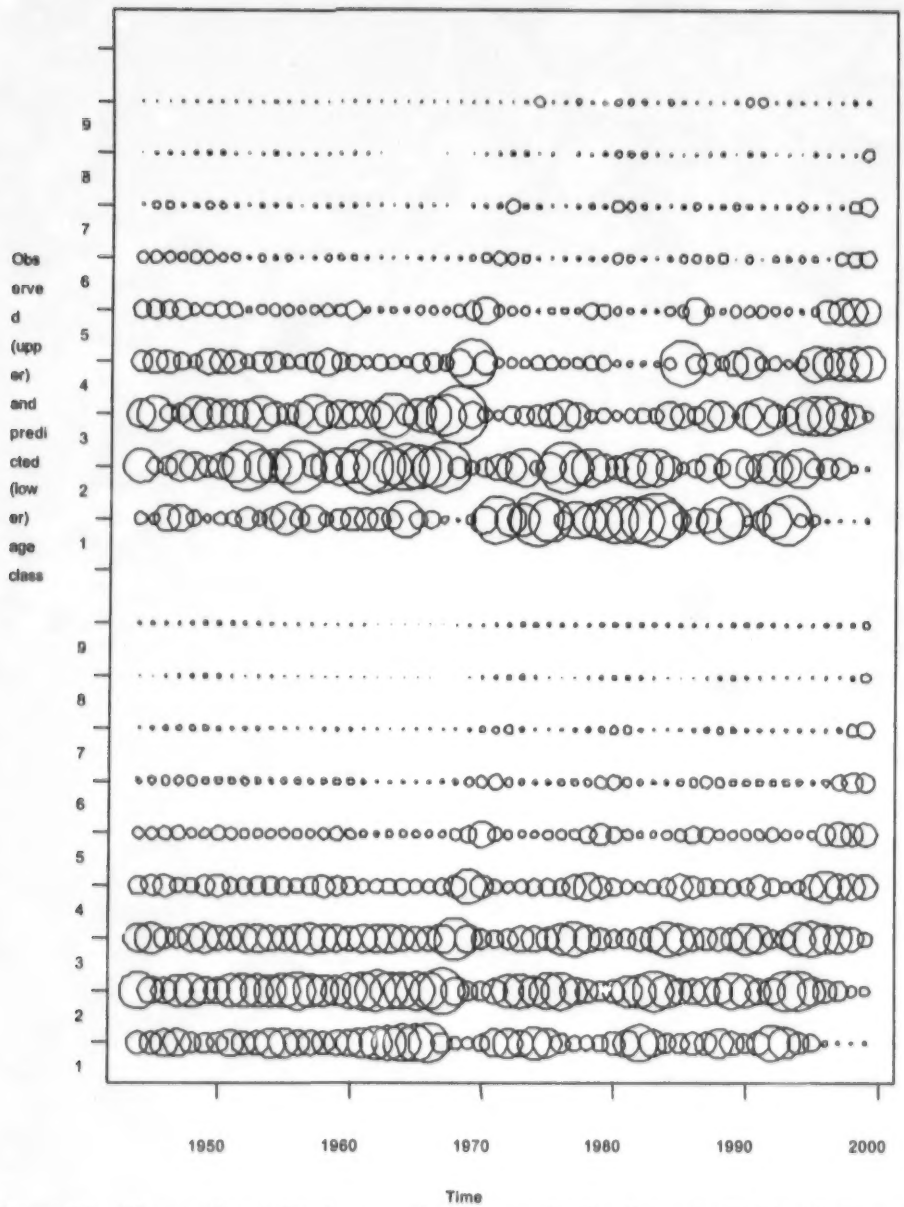

Figure 18. Observed and fitted proportions at age for English sole (Table 11, Case 1).

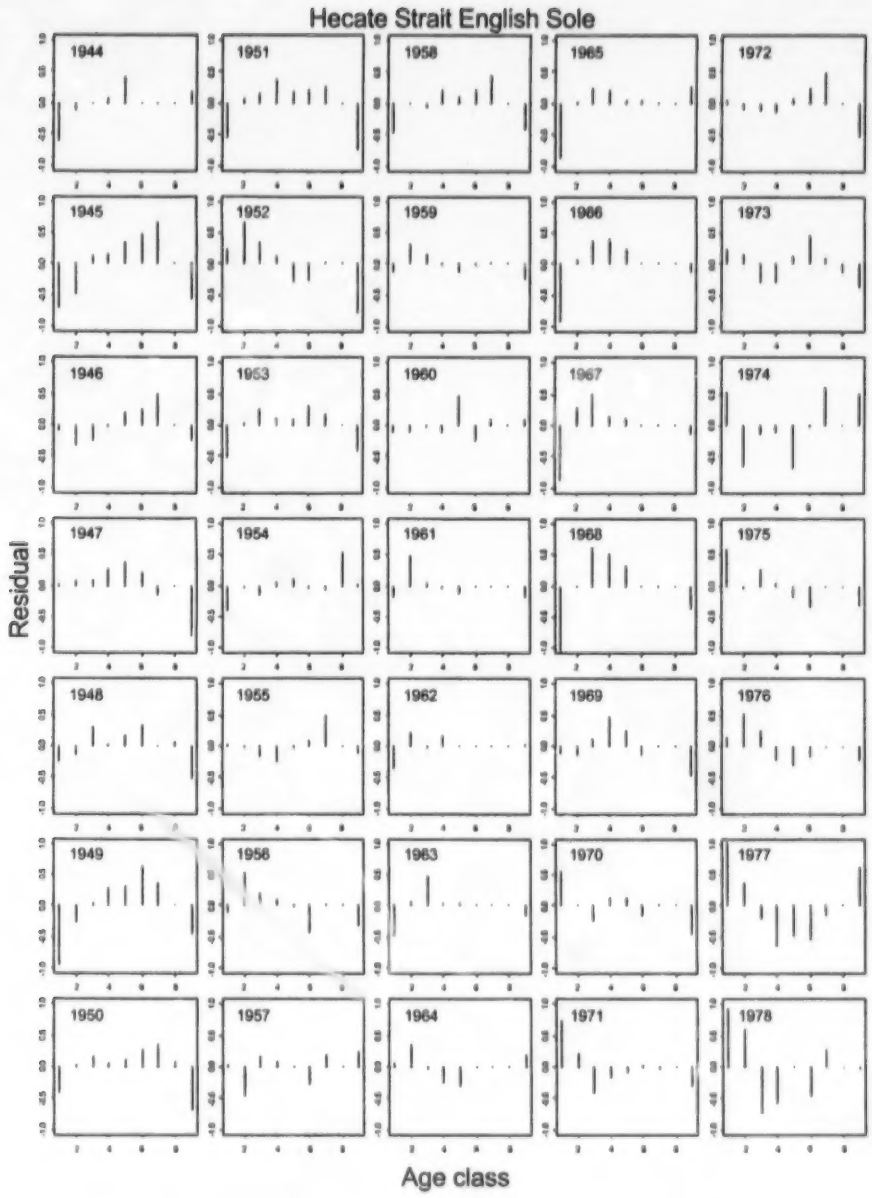

Figure 19. Proportion at age residuals for English sole (Table 11, Case 1).

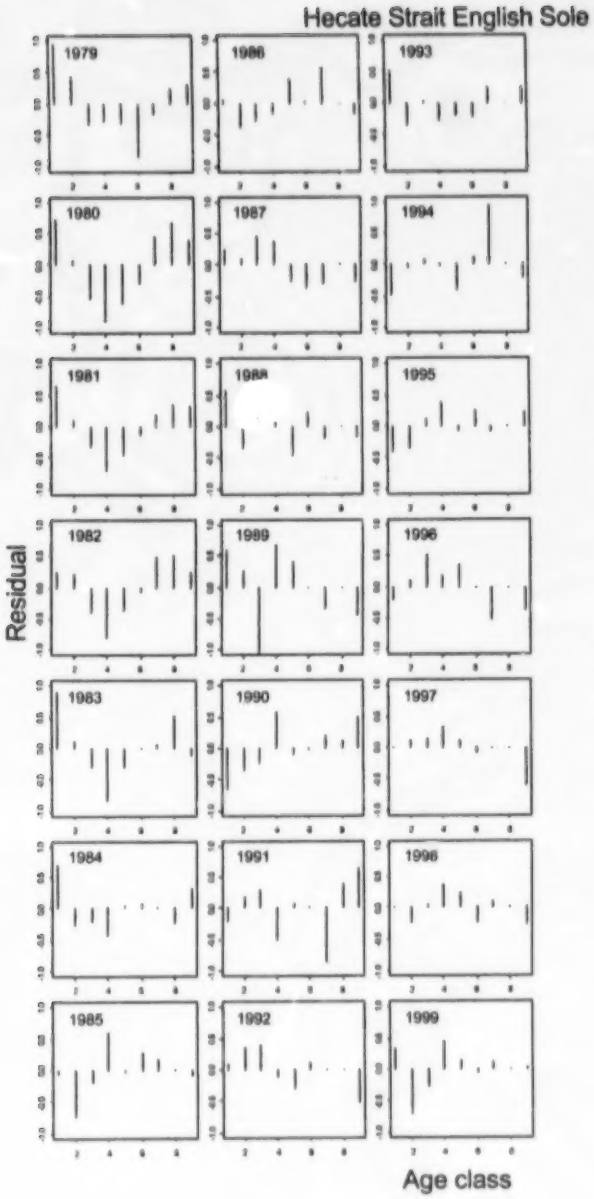

Figure 19 (cont'd).

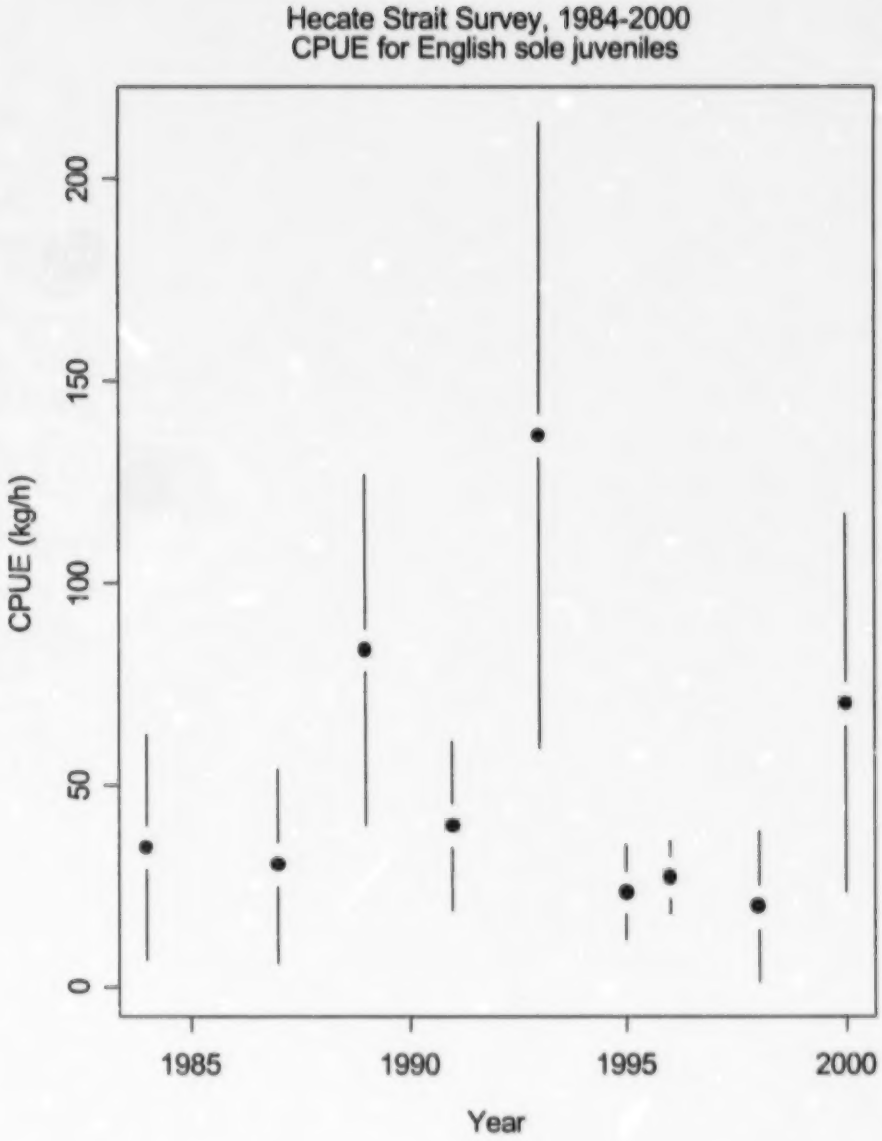

Figure 20. Mean annual catch per unit effort and confidence intervals for juvenile (≤ 30 cm) English sole caught on the Hecate Strait assemblage surveys, 1984 to 2000.

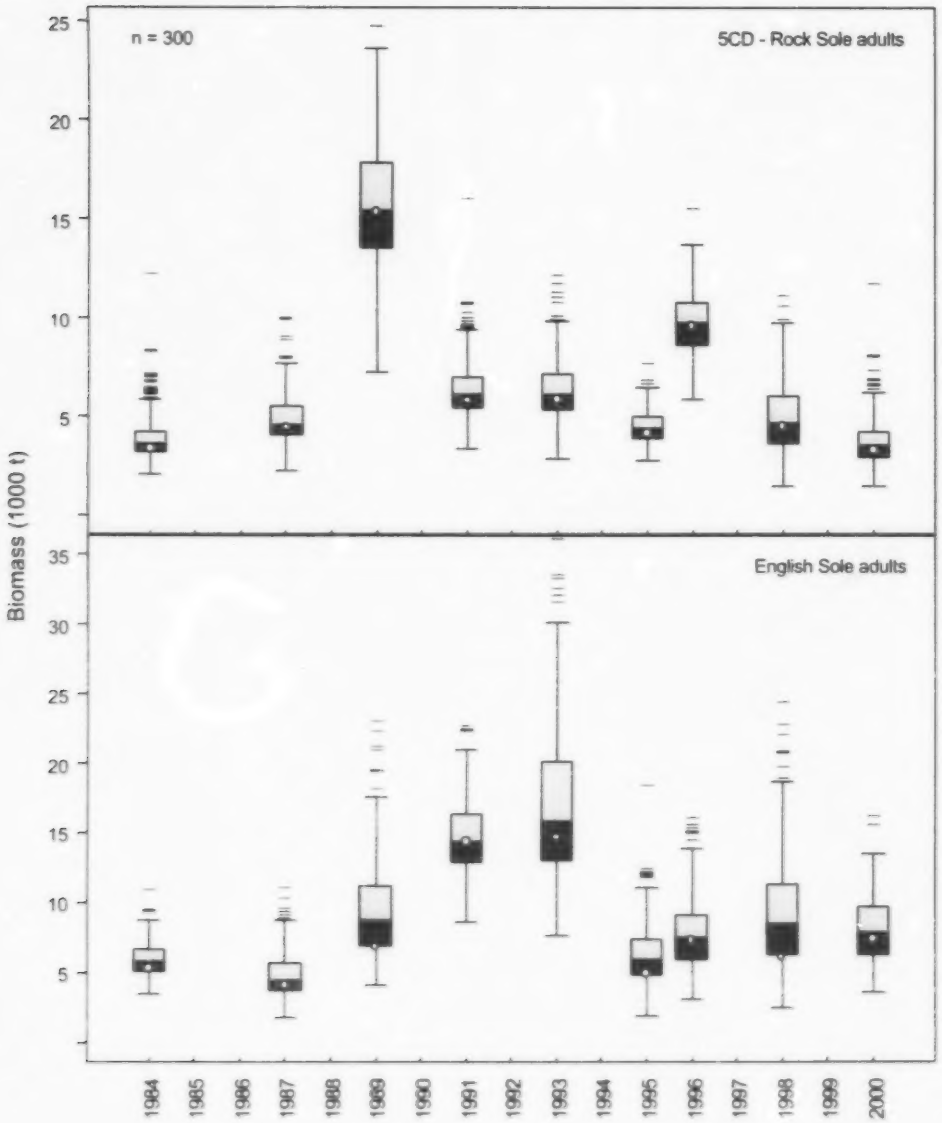

Figure 21. Boxplots portraying the distribution of 300 bootstrapped biomass estimates *B(0.1)* for rock sole and English sole, based on data from Hecate Strait June surveys. A circle in each boxplot indicates the corresponding biomass estimate. Reproduced from Schnute and Haigh (2000, Fig. 4).

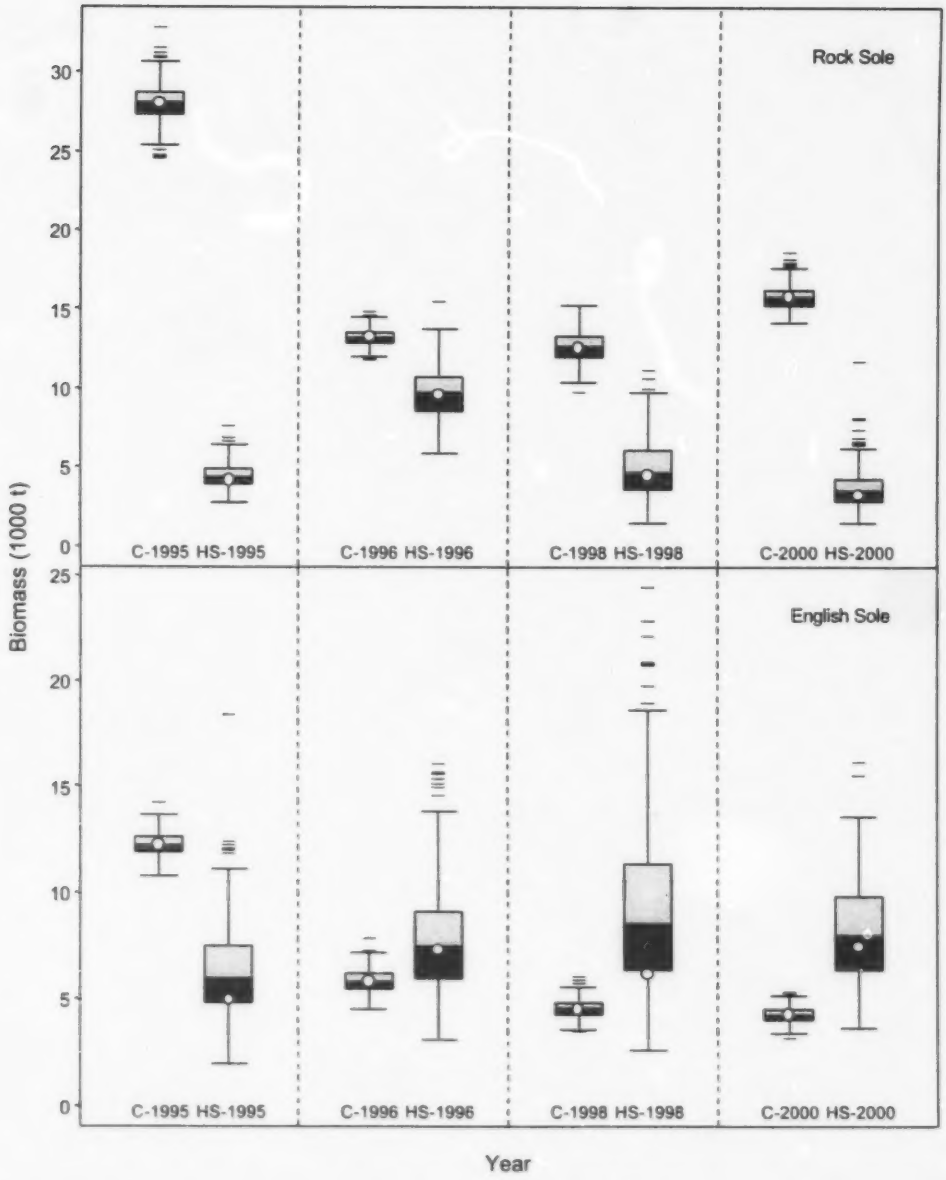

Figure 22. Comparison of bootstrapped biomass distributions from commercial and survey data. Biomass estimates *B(0.1)* come from commercial tows in the 2nd quarter (C) and Hecate Strait assemblage surveys in June (HS). A circle in each boxplot indicates the corresponding biomass estimate. Reproduced from Schnute and Haigh (2000, Fig. 6).